Mixed Reality Navigation Interface Design to Promote Urban Exploration

都市における街歩きを促進する複合現実ナビゲーションインタフェースの設計

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Waseda University

Graduate School of Fundamental Science and Engineering

Department of Computer Science and Communications Engineering,
Research on Distributed Systems

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張 伊伊

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ABSTRACT

Map navigation always plays a vital role in our daily life and impacts pedestrians' cognition of the real world. Nowadays, studies on the navigation system and map cartography assist pedestrians in navigating and providing interaction with location-based information in various scenarios. According to different pedestrian needs in navigation, the navigation system can affect the pedestrian experience from different aspects. Therefore, it is significant for researchers in different fields to discuss the specific navigational contexts to satisfy various pedestrian needs.

As a ubiquitous tool, the research on pedestrian navigation systems mainly focuses on wayfinding to aid pedestrians in finding their way in unfamiliar, complex urban environments. Thus, the navigation system requires orientating and location tracking capabilities such as GPS technology with a certain location accuracy and reliability. Moreover, studies on fundamental navigation properties also pay much attention to route planning and navigation instructions. However, except for turn-by-turn navigation, pedestrians have various purposes for using the navigation system. For instance, they also utilize the navigation to explore their surroundings information.

With the development of immersive technology like augmented reality and mixed reality, the conventional user interface of navigation systems has also been broken through nowadays. These technologies have constantly changed how pedestrians learn and interact with location-based information, especially in urban exploratory activities. The user interface design and navigation system's interaction might affect pedestrians' satisfaction and user experience from different aspects of detail. Nowadays, most of the studies and applications focus on the interface of mobile hand-held devices, while the research on the interface of head-mounted displays in mixed reality navigation to support urban exploration is not rich. Furthermore, in the context of the future smart environment, researchers in human-computer interaction need to investigate how to promote pedestrian experience in urban exploration through a suitable and comfortable mixed reality navigation interface.

Thus, in this dissertation, we focus on the interface design of future mixed reality navigation. We aim to explore the design insight for the interface of future mixed reality navigation via head-mounted displays to promote urban exploration based on user-centered design theory. We expect that this work could enrich the capability of conventional navigation, especially in future smart contexts. We designed three case

studies and conducted experiments to discuss and summarize the design insights for future mixed reality navigation to promote urban exploration.

In the first case study, we combined the location-based gamified interaction with normal navigation in mobile augmented reality and virtual desktop reality to support urban exploration. We aim to explore the interaction expectations of pedestrians during urban exploration via implemented navigations that utilize immersive technologies. We investigate and summarize the effects of the virtual interface of mixed reality navigation on pedestrians via user study experiments. Based on the user needs and requirements investigation results in case study 1, we designed an interactive virtual map interface of mixed reality navigation in the second case study. We aim to explore the role of the virtual map interface in mixed reality exploratory navigation and discuss the different levels of detail of the map to promote pedestrian satisfaction during urban exploration. Finally, in the third case study, we designed different scenarios to examine how to visualize the point of interest information for pedestrians to promote their awareness of the point of interest of location-based information.

In the end, we discuss and summarize the findings from all case studies results and suggest further directions for future studies in this area. We also list the challenges and possibilities for achieving them in future work.

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Chapter 1 Introduction

1.1 Motivation

Pedestrian navigation always plays an important role in our daily life, which could not only provide accurate navigation instructions but also support awareness of location-based information like points of interest (POIs). The study indicates that well-designed navigation systems or applications could encourage people to go outside from home, promote their human well-being through interacting with the outdoor world [1-3], and flourish the local tourism industry, city community, and various businesses [4-6]. With the rapid development of ubiquitous technologies, research on pedestrian navigation has become increasingly popular and important in various disciplines and varies from hardware, software, system, and service. Among these studies, the user interface design for pedestrian navigation is one of the necessary research topics that should never be ignored.

Some research has focused on technology to resolve the challenges in fundamental navigation capabilities, such as GPS technology, route planning method, and navigation instruction visualization for efficient navigation. However, Cartwright et al. [7] suggested that mobile maps need to be efficient and effective, and emotionally pleasing to produce a positive user experience. In addition, as people have become accustomed to accessing information via mobile devices from the Internet, the interactions between humans and their digital machines have become more diverse and complicated. Therefore, the user interface design and navigation system might affect pedestrians' experience from different aspects. Furthermore, in the future smart city environment, the function of pedestrian navigation could also be expanded and enriched to satisfy various needs.

On the other hand, recently, immersive technologies, such as augmented reality and mixed reality, have been applied in location-based services, entertainment, and the tourism industry [8-11]. Applications embedded by these immersive XR technologies can visualize the navigation instructions and display location-based information to augment the real world, promoting interaction between the pedestrian and the tourism destination through the virtual interface. Recently, an increasing number of studies on human-computer interaction (HCI) have started to pay attention to usability and preferences of user interface designs for augmented reality and mixed reality navigation [12-18]. These kinds of research constantly change how pedestrians interact with location-based information and help them learn about surrounding urban environments in an exciting way. However, although augmented and mixed reality technologies are gradually coming out of the laboratory and into our lives, they have yet to be wholly embedded in practical applications in daily navigation. There are a lot of challenges to face [19]. Moreover, these studies focus on turn-by-turn navigation via mobile devices like smartphones.

Compared with the conventional navigation interfaces for wayfinding activities, exploratory navigation pays more attention to promoting interaction and engaging pedestrians in exploration in an interesting way. Studies on exploratory navigation for some thematic urban areas for entertainment, tourism, and other location-based services have risen in recent years. The popularity of Pokémon GO [20, 21] has introduced location-based augmented reality games into the public view and achieved mainstream status. The advantages of augmented reality and mixed reality technology have attracted many researchers concentrating on this field.

For instance, some studies utilize augmented reality to display POI information by virtual marks with the category of POI for pedestrians to browse [17]. However, sometimes, there is an inability to identify off-screen POIs accurately, so there is a failure to grasp the holistic spatial information sometimes. In addition, the improper visualization of the overloaded POI information might also damage the experience and satisfaction of pedestrians in exploratory navigation. Some studies focus on interface design to explore how to engage pedestrian in city exploration [22,23] . Some studies applied location-based augmented reality games to engage pedestrians in urban exploration [24,25]. But these studies discussed little on the navigational and informational needs that provide pedestrians with efficiency and effectiveness, while they focused on game design and explored a lot for assessing the game experience. Sometimes, pedestrians also need route planning as well as the rough direction for roaming and detours as their preference. However, these works did not discuss different exploratory scenarios via location-based augmented reality applications for exploration.

Under the context of the smart city in the future, with the technology of head-mounted displays developing, research on hands-free augmented and mixed reality navigation systems via head-mounted displays is also promising. However, recent studies have yet to discuss it comprehensively. Studies on the interface design of pedestrian navigation via mixed reality head-mounted displays for urban tourism and exploration are not rich in literature. These encourage us to investigate the design consideration for exploratory navigation in urban environments via HMDs. We expect to help pedestrians to learn and access valuable information about their location, enhance the user experience, engage their participation, and even help them to establish a connection between themselves and their travel destination, community, and the urban setting in which they live.

Therefore, in this work, we attempt to focus on the user interface of future novel navigation via a head-mounted display from the perspective of human-centered design instead of technology-centered design to promote the user experience in exploratory navigation, discussing more possibilities of interaction between humans and city and thus providing more reflection and insights for the design of future mobile mixed reality navigation systems.

1.2 Contribution

- We combined location-based virtual and augmented reality with normal navigation to investigate pedestrian needs and motivation for various interface components. We summarized the interaction expectations and effects on pedestrian behavior from the mixed reality navigation interface components based on the results of the case study.
- We utilize the advantage of mixed reality to design the map interface to increase the interactivity between pedestrian and virtual 3D contents instead of just displaying the virtual marks through hand-held augmented reality navigation. The experiment results indicate that the participants showed a positive attitude toward our map interface design. We also discussed the different detail of levels of the map interface that could result in various performances and experiences in specific navigation tasks in exploration.
- We designed different POI visualization methods in specific scenario conditions to explore the interaction effect between visualization methods and scenario conditions. Then we also explored how to promote POI awareness in exploration and help pedestrians better acquire location-based information. The results indicate that pedestrians’ preference for different methods is dynamic according to conditions, and different POI visualization methods will lead to different decisions for exploration.

1.3 Structure of this dissertation

This dissertation consists of eight chapters. **Chapter 1** describes the introduction of this work and introduces the motivation, the contributions, and the organization of the dissertation. The emergence of AR and MR navigation studies has brought people's attention to the real-world interface and significantly changed the traditional method and interaction of information visualization, providing more imagination and possibilities for location-based applications and exploratory activities.

Chapter 2 describes the research background and related works in literature. Many researchers mainly focus on optimizing essential navigation functions, like GPS function, precise route-planning, and information visualization for everyday navigation. However, the research on promoting user engagement in urban exploration with mixed reality exploratory navigation needs further discussion. In this chapter, we summarize the state-of-the-art technologies related to our work and describe the difference between this work and other studies. Also, we list our research objective and research questions in the rest of this section.

Chapter 3 describes the design approach and methodology used in our case study. Overall, this work follows the perspective of user-centered design (UCD) in the HCI research area, which utilizes various user research methods, such as questionnaires investigation and interviews for user needs, workshops, etc., throughout the research process. We also describe our case studies overview according to the design theory and research methodology. We aim to use the results of each case study to discuss future interface design considerations holistically.

Chapter 4 describes the first case study and explains the study process in detail. This study aims to investigate the interaction expectation of pedestrians via immersive technologies to support exploratory navigation. We implemented two gamified navigation systems, a mobile AR navigation and a desktop virtual tour navigation. Both systems combined gamified location-based interaction with navigation interface features. In the experiment, we asked different groups of participants to have a free-walking exploration in an assigned area of the urban streets via the system respectively. Based on our results, the interesting interaction between pedestrians and the navigation could help them acquire much more information and engage them in exploration. Moreover, we summarized the interaction requirements and preferences between the pedestrian and navigation interface. We found that the preference for different interface components is dynamic according to different scenario conditions.

Chapter 5 describes the second case study and explains the study process in detail. The results in case study 1 inspire us to use MR's advantages to design interactive navigation in future intelligent environments. In this case study, we aim to explore the role and effect of the virtual map interface of MR HMD navigation on pedestrian satisfaction. First, we proposed a virtual 3D minimap in which the pedestrian can manipulate the map by zooming, rotating, and transforming. We aim to provide a holistic view of spatial and environmental information for pedestrians and increase their interaction with the virtual content. Then, to further discuss the effect of the level of detail of the minimap interface on pedestrian satisfaction in exploratory navigation, we design two levels of detail of map modes, a normal one with complete spatial and environmental information and a simplified one with filtering the irrelevant information. We used two map modes to comprehensively experiment with measuring pedestrian mental satisfaction from specific navigation tasks. The experiment results showed participants a positive attitude toward the interactive virtual minimap interface. In addition, the simplified map interface could result in better performances and lower mental demand in specific navigation tasks.

Chapter 6 describes the third case study and explains the study process in detail. In this study, we expect to explore POI visualization methods in different scenario conditions to promote the interactivity between the location-based POIs and pedestrians in exploration. According to previous work in case study 1, we found that pedestrian motivation and needs in exploratory navigation are dynamic, so the interaction between the pedestrian and navigation interface should be discussed in different scenarios. Thus, in this study, we design different scenarios of exploratory navigation with varying designs of POI visualization methods to discuss how to visualize POIs during exploration to promote POI awareness. The results indicate interaction effects between the three scenario condition levels (Target, Time, and Pull-Push) and different visualization methods. The results also suggest that the recommendation from the virtual avatar and the virtual content with mixed reality features could help and engage the pedestrian to explore much more POIs.

Chapter 7 discusses and summarizes the findings from all case studies results and suggests further directions for future studies in this area. After summarizing the findings and limitations of the above works, the challenges and possibilities for achieving them in the future are noted. **Chapter 8** makes a summary of this study. We summarize the arguments of this dissertation and the results and contributions we have identified.

Chapter 2 Background

2.1 State-of-the-art

2.1.1 Pedestrian satisfaction in exploratory navigation

Research on pedestrian navigation has a long history in different disciplines. Pedestrians always rely on navigation systems and map services for navigating and browsing information about their surroundings. With the development of information technology, the functions of pedestrian navigation are gradually enriched. As a result, the motivations and needs of pedestrians in using navigation systems and applications have become diverse according to different purposes. In [26] Fang et al. categorized pedestrians' needs into three layers based on the perspective of Maslow's theory of human needs [27-29]. They are physical sense, physiological safety, and mental satisfaction.

As shown in Figure 1, some studies contributed to the physical sense ability, such as the visual display method of navigation, and some works focused on accurate route planning and security to provide reliable navigation from the perspective of the physiological safety layer. However, the study of mental satisfaction has been ignored in some cases. Pedestrian navigation is a complex process. Except for the effect of environmental factors, pedestrians are affected by many aspects of the navigation system. Among these aspects, the navigation interface is one of the necessary aspects that should be discussed in detail. The navigation interface influences user behavior in practical scenarios, from paper maps to digital maps in mobile devices. The impact of the user interface of navigation systems on pedestrian navigation has become more complex due to the changes brought by innovations in information technology for the navigation interface and interaction methods. Thus, to enhance pedestrian satisfaction, researchers should also pay attention to user interface design in navigation from different layers and discuss the user experience in specific scenarios.

Some research focused on satisfaction during navigation. For instance, some studies utilize NASA-TLX [30, 31] and user experience questionnaires [32,33] to measure the pedestrian's perceived workload and user experience of using the interface during wayfinding tasks. However, pedestrian satisfaction and user experience vary in normal navigation and exploratory navigation. To our knowledge, the research on discussing promoting pedestrian exploration in navigation comprehensively is insufficient. Also, it should be explored in different scenarios.

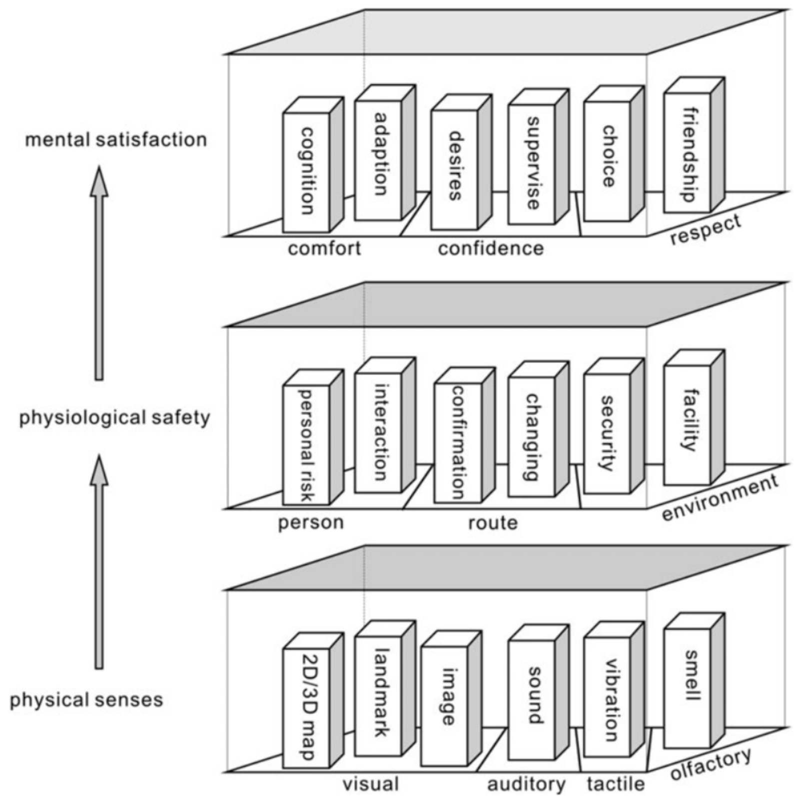


Figure 1 Three layers of pedestrians' needs [26].

Pedestrian satisfaction might be affected by the map interface in different tasks. For example, in some cases, the navigation performance of pedestrians will be affected by failure to reach a location and missing some POIs. Some studies on spatial knowledge and information acquisition. In [12], Ahmadpoor et al. emphasize the importance of mobile map design for spatial cognition. In [34], Montello summarized that the spatial knowledge of places develops in a sequence of three stages or elements: landmark knowledge, route knowledge, and survey knowledge. Survey knowledge means knowledge of two-dimensional layouts and includes the simultaneous interrelations of locations. Spatial knowledge during navigation could help pedestrians establish a cognitive map to perform orientation and navigation confidently.

Allen [35,36] categorized wayfinding tasks into three general types based on their purposes: travel between two familiar places, which is defined as a commute; travel into unfamiliar territory to learn about the surrounding environment, which is labeled as exploration; and travel from a familiar place of origin to an unfamiliar destination, which is called a quest. He suggested that different types of wayfinding tasks should be distinguished from each other and that the means used to accomplish them should be analyzed in terms of their constituent cognitive abilities. In urban exploration, all three wayfinding tasks involve different motivations and needs. For example, if a person lives in an urban area, when he or she wants to explore a familiar or unfamiliar street in that urban area, he or she might perform all three navigation tasks mentioned above.

However, mainstream navigation systems usually focus on providing the shortest route for pedestrians from one place to another place. Accurate instructions of this kind displayed on the navigation interface might occupy the attention of pedestrians so that they cannot form a comprehensive understanding of the real world, which might damage the user experience as well. Moreover, sometimes pedestrians do not need accurate route planning and navigation, which may lead to losing enjoyment and even missing some serendipity along the way, and they may view a rough direction with roaming and detours as their preference. Therefore, sometimes it is necessary to provide pedestrians with a holistic view of the spatial distribution of an urban exploration area and respectfully provide a dynamic map interface to assist pedestrians in exploring more POIs.

Figure 2 shows the taxonomy in wayfinding [37]. The author summarized different spatial knowledge during various navigational tasks. In literature, most studies focused on aided wayfinding for accurate route planning and navigation instructions. In contrast, undirected wayfinding for exploration and roaming is not widely discussed, especially in urban environments.

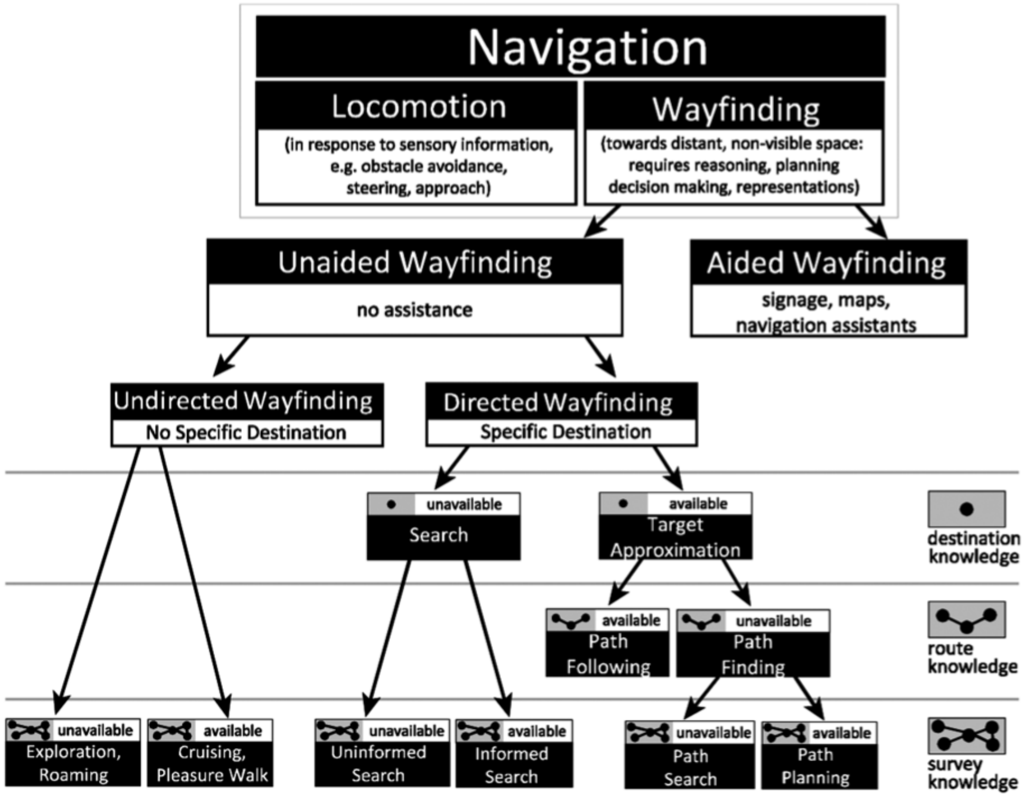


Figure 2 Wayfinding taxonomy [37].

2.1.2 Augmented reality and mixed reality

2.1.2.1 Reality-virtuality continuum

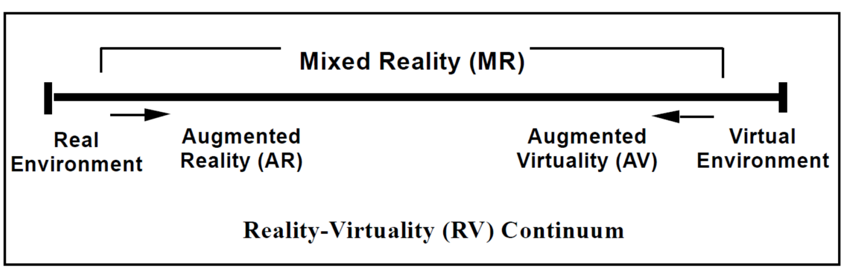


Figure 3 The reality-virtuality continuum [38].

As shown in Figure 3, the reality-virtuality continuum was first proposed by Milgram et al. in 1995 [38]. It is a continuous scale ranging between completely virtual, augmented virtuality, completely real, and augmented reality. The reality-virtuality continuum encompasses all possible variations and compositions of real and virtual objects.

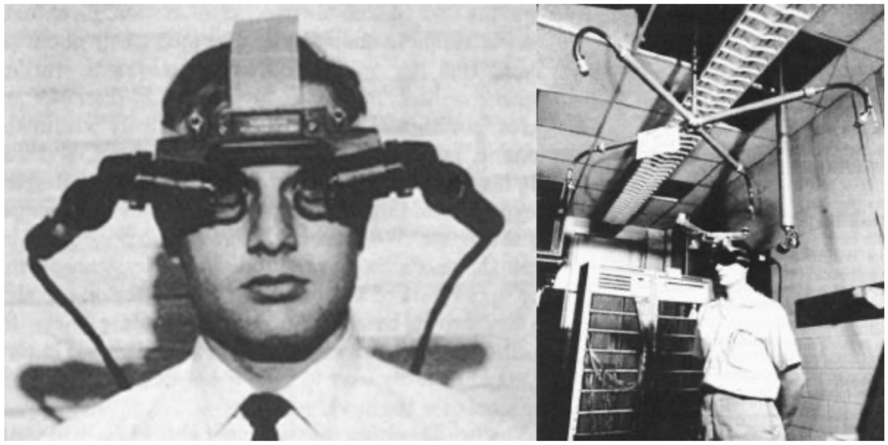


Figure 4 Optical see-through head-mounted display by Sutherland [40].

Milgram et al. defined augmented reality as a part of mixed reality. As shown in Figure 3, the area between the two extremes, where both the real and the virtual are mixed, is called mixed reality. This consists of both augmented reality and augmented virtuality, where the real augments the virtual. According to Azuma [39], augmented reality is considered a form of mixed reality, while recently, augmented reality has been seen as a method to display virtual information in the real world through anchors, which augment the physical world with virtual content. Therefore, augmented reality is a good candidate to be considered for supporting location-based activities in urban exploration. As an immersive ubiquitous technology, augmented reality can merge the virtual and the real worlds by providing real-time information based on location for the pedestrian to interact with the surrounding environment. Common augmented reality application devices are mobile terminals, such as smartphones and tablets, and mixed reality head-mounted displays. Thanks to the popularity of smartphones, the threshold for using mobile device-based augmented reality applications is currently lower than that for using mixed reality head-mounted displays.

2.1.2.2 Mixed reality head-mounted displays

In 1968, Sutherland proposed the first functional optical see-through head-mounted display for augmented reality technology [40]. As shown in Figure 4, this device was attached to the user's head from the ceiling, and it can display a three-dimensional image that changed when the viewer moved. It can make physical objects mix with virtual ones. Gradually, with other technologies, such as hardware, tracking technologies, computer vision, and computer graphics, developing, augmented and mixed reality are applied and embedded into various services and applications in numerous fields such as navigation, education, tourism, military, entertainment, etc.

In January 2015, the smart head-mounted display "Microsoft HoloLens" [41] was released. It was the first product to realize the mixed reality and put it on the market. It is standalone in the development of head-mounted display history. HoloLens requires no external connections and can be operated with hand tracking and speech input. The market has recognized it as a device that provides a new experience by recognizing the surrounding environment through an optical camera and a depth sensor and displaying content overlaid on a real space through the see-through display. HoloLens is high-performance and mainly used in industry at first. It is expected to become a smart assistant for humans' daily life in the future. With the development of wearable hardware and software on immersive technologies, humans can experience mixed reality in daily life more easily.

2.1.2.3 Current augmented reality and mixed reality technologies in navigation

In recent years, the user interface of digital map navigation constantly changed owing to the variety of interactive methods. Augmented reality and mixed reality technologies can provide researchers with more imagination in the study of interaction methods of navigation systems and applications. Currently, the study on augmented reality and mixed reality, which is applied in pedestrian navigation, is mainly surrounded by two aspects, one is navigation instruction of route-planning in wayfinding, and another is the method of augmented information visualization, which displays digital information of POIs for knowledge learning.

However, there are some challenges to augmented reality user interface information is overwhelming in a complex context, difficult to recognize self-location from the POIs, and hard to locate virtual content in the environment accurately. These challenges may reduce location awareness and user experience of exploring the surrounding environment. For instance, Brata and Liang [42] indicated that it is difficult for users to read overcrowded POIs, and few clues were illustrated to show how to get one POI location in conventional augmented reality navigation. Thus, they proposed a method to adjust the mechanism of POI display which occluded the less important ones that are farther away from the user. However, the participants of the user study still had a confusing time following and finding POI locations by augmented reality navigation only supported by step-by-step. Carmo et al. [43] combined a 2D mini-map view with an augmented reality visualization of POIs to improve information awareness, and their results indicated that the minimap is a potential method in future design. However, they focused on 2D map view in augmented reality visualization, which has not considered other presentation methods of the map interface.

Moreover, recent studies focused on hand-held devices like smartphones and tablets. With the rapid development of information communication technology, hands-free mixed reality navigation via HMD in future smart environments will gradually be applied in our daily life. However, to our knowledge, studies that pay attention to exploring the navigation interface in such kind of navigation to support urban exploration are not rich. In this work, we define mixed reality navigation as navigation with an interactive virtual interface through see-through head-mounted displays. Pedestrians could use this kind of navigation to explore a thematic urban environment. Because the interface in mixed reality display has significant differences from the smartphone interface, there is necessary for researchers to explore the design insight and detail consideration for future mixed reality navigation interfaces.

2.1.3 Research on promoting urban exploration

We define urban exploration as a pedestrian or a visitor who walks and wanders in a relatively complicated urban context, such as a tourism destination in a city street block area with various POIs. As an interface between digital information and the physical world, the digital map always plays an important part in navigation systems and should be designed to be more adaptive to pedestrian needs. The information the map provides might shape and affect relationships between places and people and give pedestrians inspiration for searching and browsing on the way.

Today's multimedia technologies provide various useful tools for specific navigation assistance, such as wayfinding, POI recommendation, and so on. Popular and common business solutions such as Google Maps [44], Google Street View [45], and Google Earth [46] permit exploring sites of cultural, historical, and geographic significance. Conventional navigation systems have benefited daily navigation with efficient orientation and location. However, the main feature of these mainstream navigation applications is providing people with precise turn-by-turn navigation, but the exploratory feature is not widely designed and integrated comprehensively.

2.1.3.1 Novel interface design for urban exploration

There are some studies that focus on the smartphone interface design for supporting POI exploration, which could be integrated into daily navigation. For example, Vaittinen and McGookin [22] proposed a radar navigation interface to visualize the POI and provide a general exploratory directional navigation for urban exploration. Sasaki and Yamamoto [23] proposed location-based augmented reality and object-recognition augmented reality to enable users to efficiently obtain directions to sightseeing spots and nearby facilities within urban tourist areas and sightseeing spot information. Some studies have also contributed to designing interesting location-based games to engage in exploratory navigation in urban environments [24].

Smart glasses and head-mounted displays are said to allow the augmentation of cities with immersive information visualizations. For instance, recent studies on augmented reality navigation focus on the visualization method of POI information on hand-held devices to support POI awareness [43]. In these studies, the navigation interface usually performs as half of the augmented reality camera and another half part of the digital map to assist recognition of virtual marks of POIs. Moreover, the map interface design in these studies is like the conventional map view of the navigation applications. On the other hand, with the development of GIS data and modeling technology, the 3D digital map plays an important role in navigation, geographic data visualization, urban management, location-based service, etc. Some studies utilized mixed reality features to augment the real world via virtual 3D content, such as 3D architectures and buildings to support cultural heritage sightseeing [47,48] in the tourism industry. Different from just adding the virtual labels and signs to the physical world through augmented reality anchors, mixed reality is a broader concept that can combine the virtual 3D objects and the real world and make the virtual elements become anchored to specific locations in the physical world to make the interactions more immersive [49,50]. With the development of technology in the context of the smart city environment, the mobile mixed reality through head-mounted display might go outside and be applied in pedestrian exploratory navigation to provide a more immersive and exciting experience. However, because the user interface in a head-mounted display is far different than in 2D mobile devices, the design of the map interface needs to be explored and discussed in detail. To our knowledge, the research on virtual interface design in mixed reality navigation is insufficient in the literature.

Gamification is the idea of using game design elements in non-game contexts to motivate and increase user activity. This idea is widely used in finance, health, education, sustainability, news, and entertainment [51]. In different situations, gamification elements and interactions are added to improve user participation, motivation, loyalty, and fun. In [52], Bartley et al. designed a mobile role-playing game (RPG) where the character evolves based on the exercises the user performs, which can motivate users to engage in physical activity for an extended period of time through the enjoyment of an engaging game. Orji et al. [53] investigate how different personalities respond to various persuasive strategies that are used in persuasive health games and gamified systems, which offer design guidelines for tailoring persuasive games and gamified designs to a particular group of personalities. Göschlberger et al. [54] also applied gamification mechanism to employees' micro-learning and considers gamification as a method to increase user promotes user engagement. Gamification can encourage user engagement and creates higher intrinsic motivations.

In recent years, the application of gamification and game design in the tourism industry has focused on gamified interactions in different mechanism designs. For instance, museum tours follow storytelling and interactive guidance, location-based check-in, sharing their travel contents, and participating in activities to earn miles or points as an incentive mechanism. In[55], Swacha et al. suggested that the key principle of the generic gamification framework for eGuide applications is provided to visitors in tourist attractions, which provides some thinking about gamification in tourism. In [56], Arkenson et al. designed a location-based game that could lead a tourist through Tainan City in Taiwan. The visitor could follow the guides to complete various tasks. In the game, visitors can experience the local culture, learn about city sites and meet local citizens who do not need to make a detailed plan in advance. However, in this research, visitors need to scan the near field communication (NFC) tag placed on a board and browse the information related to specific locations to acquire the site's introduction and tourism guidance. C. Pang et al. [57] designed a game to help people strengthen their sense of community. Players in this game can also create geo-tagged posts to describe and share community-related information. These designs provide novel game designs for non-game daily contexts to help visitors explore the city street, but they did not embed the augmented and mixed reality features into the application. In [58], Rubino et al. developed a game for a historical museum to introduce its history to teenagers. It made a narrative and game mechanics to engage visitors' motivations to explore the museum. In [24], Nóbrega et al. designed a narrative story for travelers to explore the city and learn its history. Moreover, they developed location-based augmented reality games to provide the traveler with an interesting interaction. Paula et al. in [59] designed a mixed reality location-based game in physical city streets. Table 1 illustrates a summary of gamification research in travel and tourism.

Table 1 Summary of gamification research in travel and tourism

Related Works	*System/Application/Service*	*Feature1*	*Feature2*
Caroline Arkenson (2014)	Tag and Seek Leads a traveler through Tainan city in Taiwan.	Location-based game for travel	The traveler's task is to find virtual friends who are hiding at different sites in the city.
Paula Alavesa (2015)	SAG Explore the real streets via mixed reality mobile phone.	Location-based game mixed reality mobile phone game	Tagging predefined locations around the city to claim their ownership and busting nearby players of competing gangs.
Irene Rubino (2015)	Gossip at palace Developed for an Italian historical residence museum.	Location-based game travel augmented reality mobile phone game Integrated a storytelling approach	Narrative and game mechanics to foster young visitors' motivations to explore the museum and facilitate their meaning-making process.
Armir Bujari (2017)	Phototrip Travel suggestions and recommendations	Identify POI by gathering pictures and related information from Flickr and Wikipedia Provide the user with suggestions and recommendations service	Exploited social networks, crowdsourcing, and gamification to involve users in the process of improving the response quality of system
R Nóbrega (2017)	Unlocking Porto An exploration application was designed for the city of Porto.	Location-based game travel Story engages the player into the main sights	Following an augmented reality path while playing small games.

However, studies in the entertainment and gaming industries have only recently focused on the hedonic needs of users in hybrid spaces. These studies go beyond navigational and informational requirements that serve efficiency and effectiveness to assess the experience of pervasive playfulness. In addition, little is known about designing location-based augmented and mixed reality games for urban contexts via HMDs.

2.1.3.2 Recommendation system for urban exploration

Currently, users have two ways to acquire location-based information, one is through search engines, and another is referring to online maps marked with POI information. In the former one, pedestrians have access to a large amount of information based on keyword searching, which is challenging to pick out the POI they prefer from a list of search results. According to the map interface, although users can obtain the distribution of POIs from maps based on their geolocation, they need help accessing detailed information. As a result, recommendation systems are studied to face these challenges. The recommendation system could provide pedestrian with various methods to narrow the search results so that they can choose the POI they might be interested in exploring. The recommendation for exploration via navigation mainly focuses on recommending the exploratory routes and the POIs in different algorithms design.

There are already numerous services and systems that allow users to interact with geo-based content from the Internet. For example, users often generate and share their travel experiences on various social networks. Some studies utilize multimedia data mined from location-based applications and other social media to extract the potential POIs for pedestrians. For example, these systems can visualize the popular tags of a geographic region to support exploration based on popular location information and personal preference.

Methods to recommendations are usually related to context awareness, and their combination presents search results. Ye et al. [60] compared the effects of historical behavior, geographical distance, and social networks based on user similarity in a POI recommendation task. Baltrunas et al. [61] introduced a context-aware POI recommendation system that considers contextual factors, such as distance to the POI, temperature, and user's mood. Perebner et al. [62] proposed a travel guidance system that automatically identifies and ranks landmarks for travelers from online photos and guide information. For this and similar systems, most of them aim to provide recommendations of tourist spots based on the user's past behavior or the popularity of the destination. In addition, some studies proposed methods to extract the social dimensions of people in different places. In [63], Huang et al. designed a social recommendation system is introduced to give personalized suggestions related to the POI of the user's location. After filtering the users, the system uses information from websites, social networks, and user opinions to provide recommendations for POIs.

Regarding route planning, it is also a popular research topic in exploratory navigation. Unlike turn-by-turn route planning for formal navigation, route planning in exploration aims to provide pedestrians with a more interesting exploratory route. In [64], Herzog et al. proposed a recommender to support travelers in identifying the most attractive POIs and combine the POIs along a route. Some studies also used the photos collected from the SNS to make a route marked by excellent photographs as recommendation. These works involve the algorithm design to calculate the route for exploration recommendation. On the other hand, nowadays, some personalized recommendation systems could also collect the preference and conditions of the users and generate numerous routes for users to choose from.

2.1.3.3 Summary research on promoting urban exploration

Based on the above research investigation on promoting urban exploration, we found that researchers in this area are focusing on various methods to support pedestrian engagement during urban exploration. However, the main devices in these technologies are mobile devices such as smartphones and PDAs. Moreover, the virtual interface of augmented reality and mixed reality navigation via the HMDs mainly focuses on the virtual label to display the POI information based on geographic location. On the other hand, more research on engagement and pedestrian experience is needed.

Engagement is considered one of vital concepts to evaluate pedestrian satisfaction and user experience of location-based augmented reality and mixed reality in tourism and urban exploration. In addition, the necessity of user engagement as a form of co-creation of experience and value has also been highlighted as a crucial idea for services and applications. In the context of HCI, interactivity is central to user engagement. Researchers at HCI emphasize the importance of designing compelling experiences beyond usability to capture users' attention and keep them focused on an artifact or activity for a period. In urban exploration, the "engagement" can be defined as promoting interaction with the location-based information through virtual interface. [65-68].

To our knowledge, the interface design for future exploratory navigation to promote the pedestrian experience and engage them in participatory is not rich. The exploratory navigation design should be explored to meet pedestrians' requirements to understand the experience of exploration and engagement comprehensively.

2.2 Research objective and research questions

Based on the investigation of the literature review, this dissertation aims to explore the design insight for the interface of future mixed reality navigation via HMDs to promote urban exploration based on user-centered design theory.

To achieve the research objective, in this dissertation, we focus on three primary research questions (RQs):

- RQ1: What are the pedestrians' needs and preferences for virtual interfaces in urban exploration?

  In this research question, we expect to explore the effects of the interest-based virtual interface of mixed reality navigation in urban contexts. We investigate the user requirements to consider the different interaction expectations with the interface components during exploration.

- RQ2: How can we design the virtual map for promoting urban exploration?

  As a vital part of the interface in navigation, we explore the role of the virtual map interface in mixed reality exploratory navigation and discuss the level of detail of map design to promote pedestrian satisfaction during urban exploration.

- RQ3: How can we design the POI visualization method for promoting urban exploration?

  To consider how to visualize the POI information on the navigation interface to help pedestrian learn their surroundings better. We should specify how to combine the virtual world seamlessly into our physical environment, making them less intrusive and more beneficial for pedestrians. Thus, we expect to discuss how to design the interface to display POI information in a more comfortable and natural method. We utilized different types of the virtual map interface to discuss how to design a better interaction for receiving different types of POI information.

Chapter 3 Design approach and research methodology

3.1 Design diagram

In this dissertation, we aim to depict the interface design picture of future mixed reality navigation via HMDs. To answer the research questions, we proposed three case studies surrounding two interface components: map interface design and POI visualization design.

Firstly, we added the gamified interest-based feature to the conventional navigation system. The system combines the formal navigation function and the location-based gamification interaction. We conducted a free walking experiment task to observe the interaction between the participants and the interface components during exploratory navigation.

Based on the observation and interview results in case study 1, we consider two aspects of mixed reality interface design respectively. The first one is how to design the virtual map interface with different levels-of-detail information to support urban exploration. Another one is how to design visualization methods and interaction methods for POIs to promote experience during exploration, shown in Figure 5.

Finally, based on the design consideration for map interface and visualization and interaction for POIs, we summarized the design framework for future mixed reality interfaces in urban exploration.

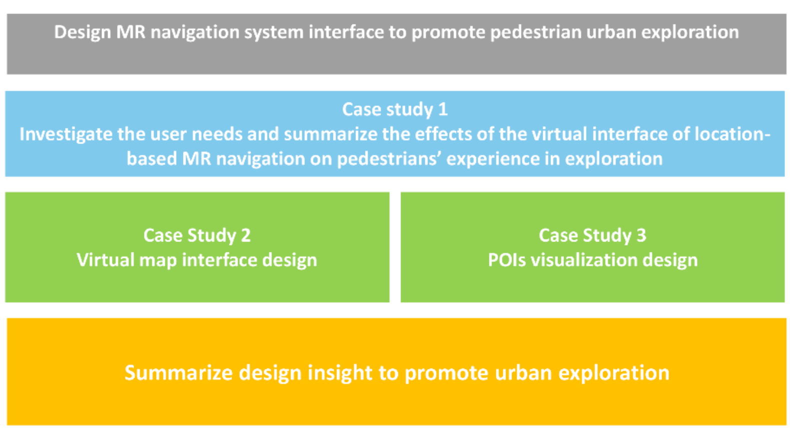


Figure 5 Design diagram of mixed reality interface design in this work.

3.2 Research methodology

3.2.1 User-centered design

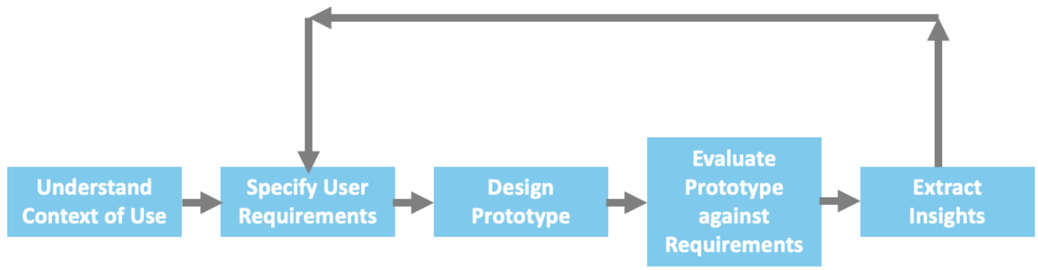


Figure 6 Standard UCD process.

User-centered design (UCD) [68] is an iterative design process and a framework of tools that is applicable to a wide range of domains in human-computer interaction (HCI). Figure 6 shows a standard UCD process. User-centered design is based on the understanding of a user, their demands, priorities, and experiences when used, is known to lead to increased product usefulness and usability as it delivers satisfaction to the user. From a HCI perspective, investigating new technologies encompasses a multitude of dimensions that surround the usage and adoption of daily used technologies [69]. In this work, we use UCD as the primary research method due to its multiple advantages in rapid prototyping, evaluation, and knowledge extraction. The use of UCD allows for the rapid development and evaluation of various specific requirements and criteria without emphasizing the full prototype. Therefore, in addition to conducting various UCD-based assessments, the developed prototypes reflect the specific design and assessment requirements and, therefore, do not reflect all design or implementation requirements.

The research conducted in this dissertation is based on the UCD process. The research methodology adopted in this dissertation builds upon the standard UCD process, shown in Figure 4, by including an extra step for analyzing and extracting the various case studies. The research is conducted iteratively and in accordance with the UCD method.

3.2.2 Human-city interaction

The developing ubiquitous computing technology in the city allows human-infrastructure-technology interactions in urban areas to cross the real-virtual intersection. The new data layer in the city allows for numerous novel applications. For example, citizens can obtain information about traffic, stores, and building works to navigate through the city.

In a connected city, augmented reality and mixed reality technologies can provide context-aware interaction capabilities for its residents, city staff, private companies, and local governments. Human-city interaction is the intersection of these three paradigms. Human-city interaction further extends the concept of human-computer interaction related to the usability and design space of specific computing devices into user-centered system interfaces in smart cities. For city-wide interaction and high user mobility, augmented reality and mixed reality smart HMDs are considered excellent candidates for providing immersive urban interfaces. As a result, user interaction design follows this paradigm and evolves toward wearable headset computers [70]. Therefore, in this work, we plan to explore the interface design of mobile mixed reality exploratory navigation based on the design consideration of both human-computer interaction and human-city interaction to explore more possibilities of interaction between the pedestrian and city.

3.2.3 Overview of three case studies

In case study 1, we designed interest-based gamified features for formal navigation to explore user interaction expectations and the effects of interface components on user experience. Based on our results, we found that the different interface components will affect the pedestrian experience in exploration. Also, the expectation and requirements are dynamically changing during the exploratory navigation. The observation and interview results in case study 1 help us to summarize the needs and preferences of pedestrians during urban exploration. Based on the results of case study 1, we plan to discuss the different interface components via case study 2 and case study 3.

Based on the insight investigated via the case study and inspired by the development of mixed reality technology and the application of minimap mechanisms, in case study 2, we aim to explore the role and effect of the virtual map interface of mixed reality HMD navigation on pedestrian satisfaction. First, we proposed a virtual 3D minimap in which the pedestrian can manipulate the map by zooming, rotating, and transforming. We hope to provide a holistic view of spatial and environmental information for pedestrians and increase their interaction with the virtual content. Then, to further discuss the effect of the level of detail of the minimap interface on pedestrian satisfaction in exploratory navigation, we design two levels of detail of map modes, a normal one with complete spatial and environmental information and a simplified one with filtering the irrelevant information. We used two map modes to comprehensively experiment with measuring pedestrian mental satisfaction from specific navigation tasks. The experiment results showed participants a positive attitude toward the interactive virtual minimap interface. In addition, the simplified map interface could result in better performances and lower mental demand in specific navigation tasks.

In case study 3, we expect to explore POI visualization methods in different scenario conditions to promote the interactivity between the location-based POIs and pedestrians in exploration. According to previous work in case study 1, we found that pedestrian motivation and needs in exploratory navigation are dynamic, so the interaction between the pedestrian and navigation interface should be discussed in different scenarios. Thus, in this study, we design different scenarios of exploratory navigation with varying designs of POI visualization methods to discuss how to visualize POIs during exploration to promote POI awareness. The results indicate that there are interaction effects between the three scenario condition levels and different visualization methods. The results also indicate that the recommendation from the virtual avatar and the virtual content with mixed reality features could help and engage the pedestrian to explore much more POIs.

Chapter 4 Case study: pedestrians' needs and preferences of virtual interface

This chapter is written based on the part of the section in the conference paper [71] .

In this chapter, we design two interactive tourism guidance navigation as two case studies to investigate the interaction expectations of pedestrians during urban exploration. We recruit new residents who have just moved to a new urban area to explore an unfamiliar environment via our systems. We hope to explore the interactions between the pedestrian and virtual content, as well as the interaction between the pedestrian and real tourism destinations.

4.1 Preliminary study

To understand the demands of new residents for urban exploration supported by mobile technologies, we first conducted a questionnaire survey on 14 international students (13 males, average age =23 years) from China who were going to live and study in Tokyo in the future. All of them had come to Tokyo for less than two months (1.8 months on average). We asked all the participants to answer a questionnaire and participate in a short interview with some questions. In addition, all participants thought that map navigation was the most used mobile technology in their exploration to help them know more about the new city they live in, as shown in Figure 7.

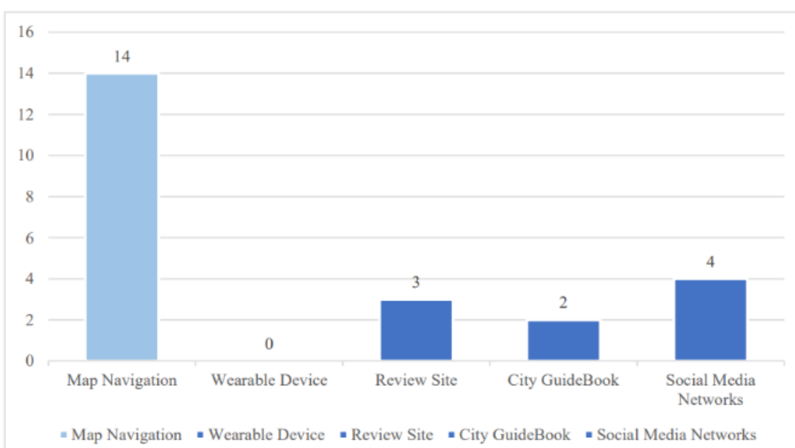


Figure 7 The answer to question: What smart technology do you commonly use to learn more about the new city or new community in which you live? (Choose 2 options).

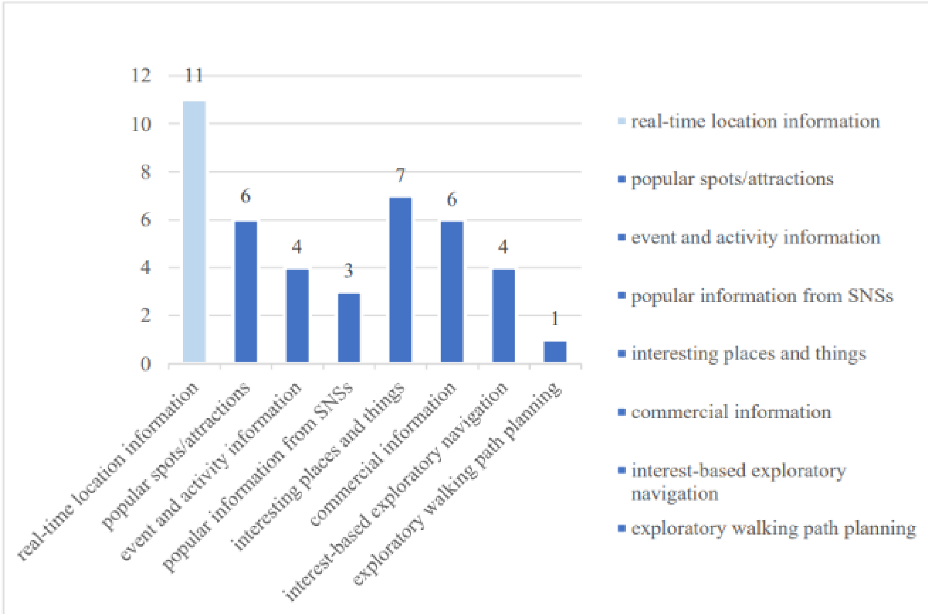


Figure 8 The answer to question: What information or assistance do you want to acquire from smart mobile devices during city walking and exploring? (Choose 3 options).

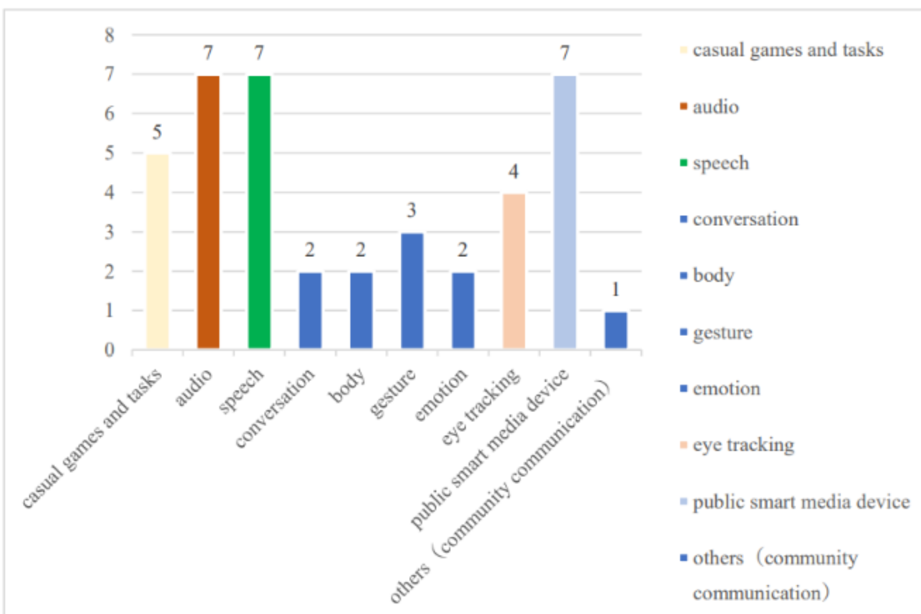


Figure 9 The answer to question: Which interaction do you prefer to support your city walking and exploring? (Choose 3 options).

In the survey, we learned that participants faced many challenges and difficulties while exploring the city, as shown in Figure 8 and Figure 9. For example, some participants said they paid too much attention to the navigation interface and neglected other information, such as signs on the road.

Participant P2 said that when using a traditional map to navigate, there was too much useless information or places that the user did not want to be overlaid, resulting in visual redundancy. Another participant (P4) reported that when he wandered in an area, he was unable to return to the previous location and route because he was exploring other paths or locations. Some participants also stated that the real-time information provided by the navigation systems or applications currently in use was sometimes inaccurate. Based on the survey results, we summarized the ways in which new residents explore their basic needs in the city they live in and interact with mobile technologies. We developed two systems for a case study for observation and further study. We will introduce these two systems and describe the experimental details in later sections.

4.2 Study 1: Virtual reality city tour

4.2.1 Introduction

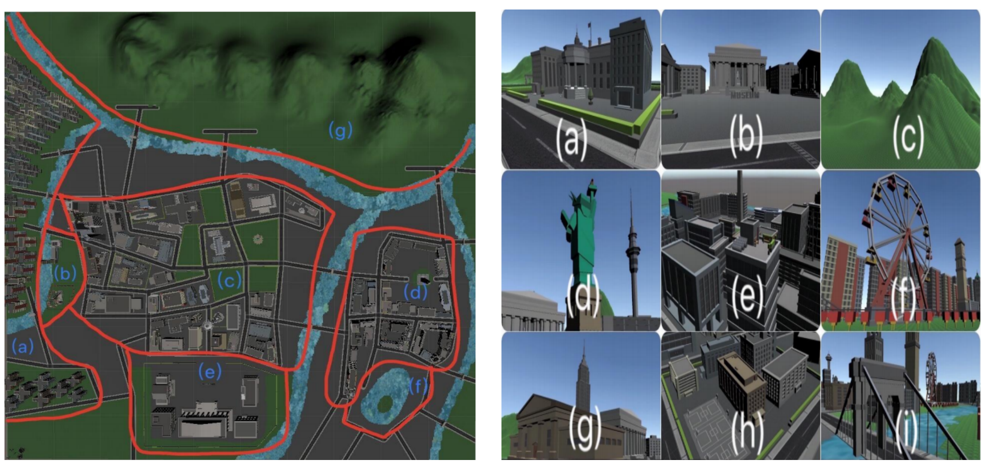


Figure 10(Left) Overview of the city distribution, and (Right) examples of buildings and spots (The typical spots and buildings in the city include the following: (a) a government building, (b) a museum, (c) surrounding mountains, (d) a statue at the city center, (g) an art museum, (h) a school, and (i) a bridge over a river).

Virtual reality city exploration can simulate real city blocks while walking and break through the constraints of time and space; thus, we can use virtual reality city exploration to test user exploration activities and services in the virtual world. In addition, virtual reality city exploration can also be applied when a user cannot go outdoors but wants to simulate a roaming exploration in advance so that they are familiar with the routes and atmosphere and learn more local information at home.

It is a challenge for a new resident to quickly obtain a holistic view of the city blocks he or she lives in, so we are approaching this challenge by designing a virtual city tour, as shown in Figure 10 (Left). In our system, gamification components and virtual interaction with the real-world location are designed to engage new residents in exploring the entire city. To encourage users to actively explore fictional cities in virtual environments, interactive icons and related interfaces are applied, as shown in Figure 10 (Right).

4.2.2 Implementation and experiment

To implement virtual exploration, a virtual environment is required. In the beginning, a mirrored scene according to reality is designed. To construct a virtual city scene, the Unity3D [72] platform is used. The virtual city consists of residential areas, commercial areas, centric areas, museums, an amusement park, a monument, a lake, rivers, and surrounding mountains, as shown in Figure 11 (Left). Buildings and infrastructure constructions, including roads, bridges, and flowerbeds, are prefabs available from the material library. A statue stands in the center of the centric area. An art museum, a government building, and a school are in a centric area. A TV station and signal tower are also included. Some detailed scenes and exploration interactions are illustrated in Figure 11 (Right).

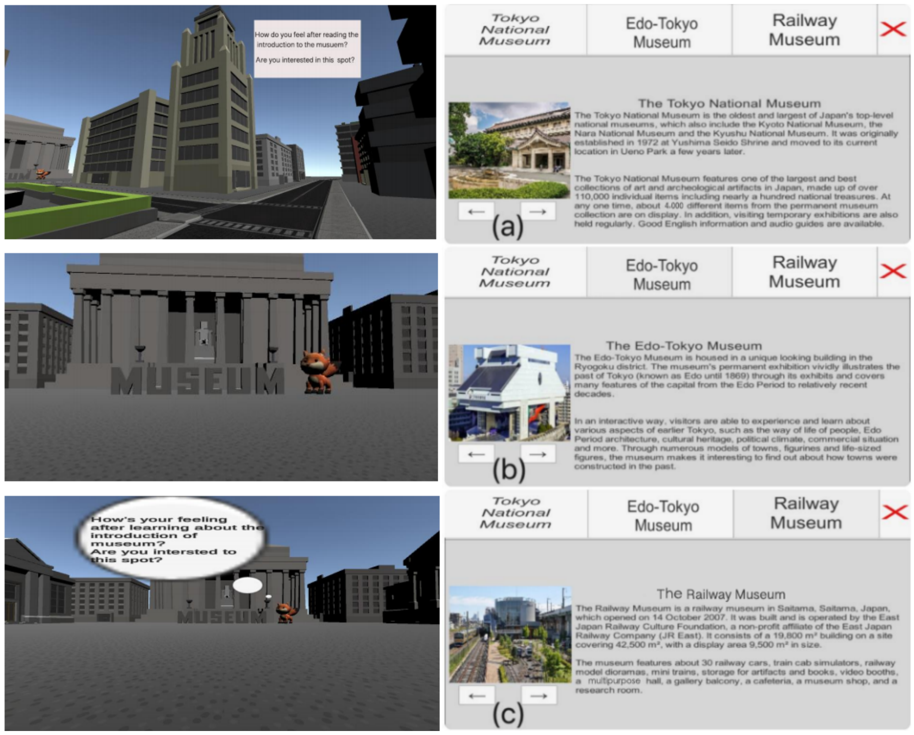


Figure 11(Left) Real-world location-based interaction and navigation in the process. (Right) The related interfaces of the museum. The related interfaces of the museum model include the following: (a) the Tokyo National Museum, (b) the Edo-Tokyo Museum, and (c) the Railway Museum. Each page includes four images of the introduced museum, which could be switched through the left/right arrows.

To test the interaction between users and the real geographic location information in the virtual reality city during walking and exploration with our system, we invited 11 participants (7 males, average age = 24 years) to experience the virtual city exploration. Of the 11 participants, 63.6% of them had not used virtual reality systems or applications to explore the city. In the experiment, participants will explore an unfamiliar city block based on location and interest-based navigation in the scene, learn relevant knowledge, and complete the tasks in the exploration activity. After the experience, each participant will answer the questionnaire shown in Table 2 for experience satisfaction evaluation. The results of the questionnaire are shown in Figure 12. The overall mean value for each question is high.

Table 2 Questionnaire for experience satisfaction evaluation.

Q1. Do you think the system is useful?
Q2. Do you like to explore and interact in the city streets using gamified interaction with a real destination?
Q3. Do you think this type of incentive mechanism is useful and encourages you to continue to play and explore more?
Q4. Do you like using this system?
Q5. Did you enjoy the experience?
Q6. Were you interested?
Q7. Were you impressed?
Q8. Do you think you were attracted?
Q9. Do you think these functions can meet your demands?
Q10. If it is perfect enough, would you like to use the system in the future?

Figure 12 Results of the experience satisfaction evaluation of experience satisfaction evaluation for the system.

4.2.3 Discussion

Based on user study results, most participants considered this exploration navigation to be useful (average value = 2.9), and they liked using it to learn more about the city streets (average value = 3.6). Most of them are willing to use it if it is perfect enough in practice (average value = 3.9).

Participant P3 stated that "the system should design a classification in advance for different demands of people who come to a city, such as, to live, to travel, to study, or to see a doctor and so on. For example, you can do a preliminary classification at the beginning of the exploration, explore some options...". More than one participant suggested that if the roads and facilities of a virtual city were fully simulated in the real world, the system could be used by people who have difficulty getting out or who want to experience a route ahead of time. Participant P10 said that if he uses a virtual reality city exploration system, he will prefer to interact with other players online, which inspired us to consider establishing a social network in the future.

People who are interested in exploring will want to use the system themselves. This group of people may use the system to see the cities they want to visit, plan their routes ahead of time, do their homework, and eventually actually experience the city. However, for those who prefer to stay at home rather than go out, using virtual reality to explore cities offers more possibilities and perspectives on their lives. In other words, further experiments and discussions are needed on the classification of people using such systems.

The participants supposed that it is more important to combine the virtual world and information with the real-world location, which led us to consider how to add more interaction between the virtual world and reality. At the same time, in the questionnaire survey and interview, we learned that different people have different purposes for using virtual reality systems to simulate real city tours, so they also have different demands for functions and user interfaces. For example, one participant suggested that, for specific roaming purposes, the location information could be simplified on the map display to highlight the target location information he needs.

After a user study test on virtual reality city tours, we reviewed our navigation design and proposed a gamified augmented reality navigation system to support user interaction during practical exploration.

4.3 Study 2: Gamified augmented reality navigation system

4.3.1 Introduction

To promote user experiences while city traveling, this research proposed an augmented reality travel guide system based on a role-playing game (RPG), which combines an incentive mechanism of gamification and real-time geographic location services to provide users with appropriate travel information interaction without disturbing the user's own exploration and roaming. The system was designed to provide travelers with a more memorable, highly engaged, and satisfying travel experience. The functions of the system, which allow travel experiences to be more attractive and impressive so that the memory becomes clear, coherent, and memorable, will be described in detail below.

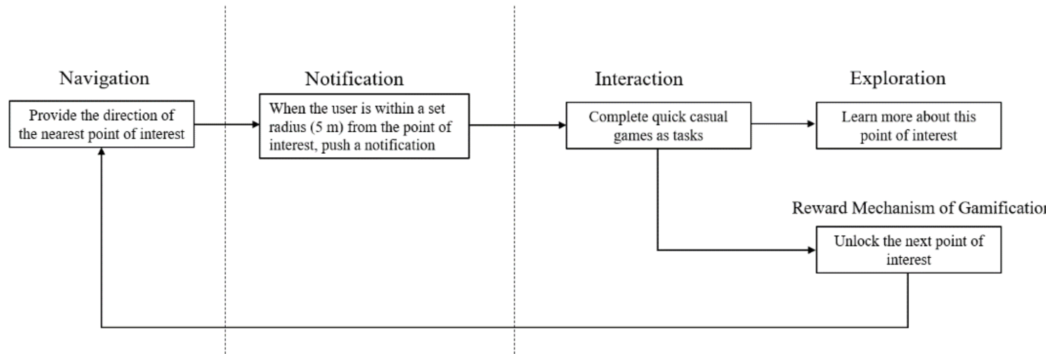


Figure 13 The mechanism design of the system is illustrated by a cycle consisting of four stages. They are the following: navigation, notification, interaction, and exploration.

Based on the analysis of the needs of travelers, the system designed in this research, based on ensuring that the user is provided with a real guide to attractions, adds role-playing gamified dialogue interaction and incentive mechanisms to improve the system' s interest and immersion. The mechanism of the system, which aims to engage pedestrians in exploring POIs one by one, is illustrated in Figure 13. In terms of the navigation stage, we provide the direction of the nearest POI and display its distance from the pedestrian. We set a series of hotspots in destinations based on real geographical coordinates (using GPS). When the user is within a set radius (5 m) from the center of the POI, the system will send a notification, as shown in the figure. To encourage pedestrians to explore many more POIs, we designed interactions and explorations with gamification reward mechanisms. In a manner like the conversation system of an RPG (role-playing game), users can complete some game tasks followed by conversation and interaction with virtual character assistants. A gamified reward mechanism would engage pedestrians to trigger navigation to another close POI. The screenshots of our system are illustrated in Figure 14 and Figure 15.

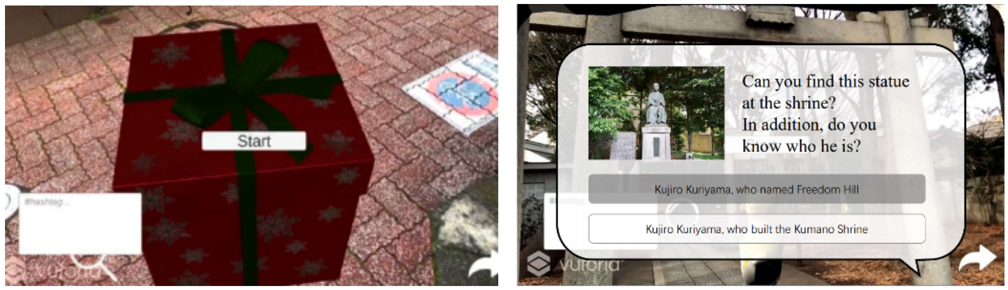


Figure 14 A quick casual game for pedestrians to learn more information about this location.

Figure 15 Augmented reality navigation and game conversation are activated by a virtual assistant (a virtual cat character).

4.3.2 Implementation and experiment

Figure 16 Application UI interface.

The system was developed using the Unity3D [72] game engine. The augmented reality features are supported by Vuforia SDK [73]. The application is installed on an iPhone smartphone with the iOS12.1.4 system. The system UI interface is shown in Figure 16.

To evaluate user experiences (usability and engagement), we conduct a field experiment as a preliminary user study. We invited 5 participants (3 female, average

age=24 years) to use our system to explore a real city block destination named Jiyūgaoka. Jiyūgaoka is a residential area located in Setagaya City, Tokyo. It is surrounded by various shopping streets and residential districts. Various stores are hidden in the narrow streets that are popular with residents and visitors. In addition to colorful and interesting shops, there are also very famous places of interest, including the ancient Kumano Shrine, a miniature version of Venice, and an old Japanese-style café Kosoan. We selected several popular locations located in Jiyūgaoka district and obtained their GPS coordinates (latitude and longitude) from Google Maps as hotspots for the experiments. The map of Jiyūgaoka is illustrated in Figure 17 (Left). It consists of coffee shops, bakeries, shopping malls, restaurants, beautiful architecture, and other types of charming POI.

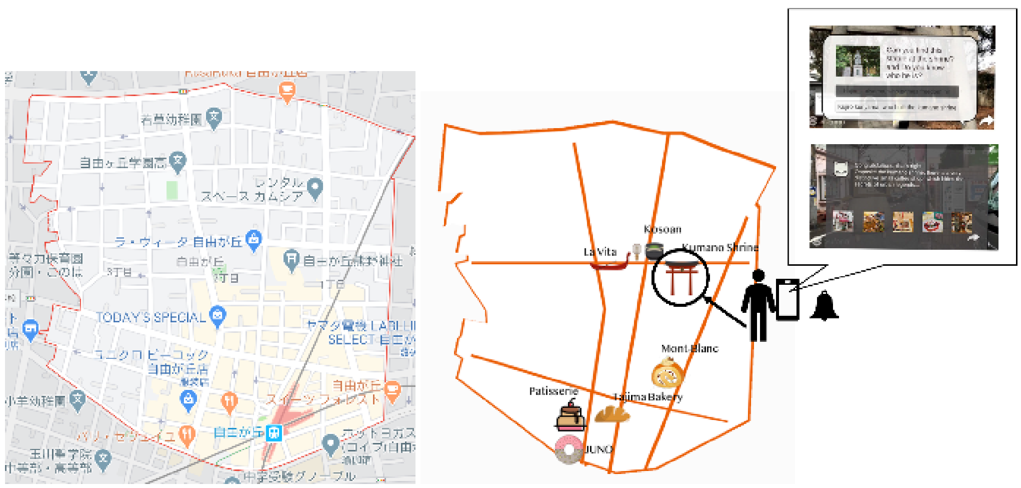


Figure 17 Left: map capture of Jiyūgaoka from Google map; right: location-based hotspot trigger function.

We asked participants to explore all the POIs using our system. When the participant was close to a POI, a series of activities would be triggered, as shown in Figure 17 (Right). After the experiment, each participant was asked to answer a questionnaire. Then, all participants were invited to participate in a semi-structured interview. In the interviews, all participants were asked to describe their experience and give some comments and suggestions on the functions of the system. The progress of the user study is illustrated in Figure 18.

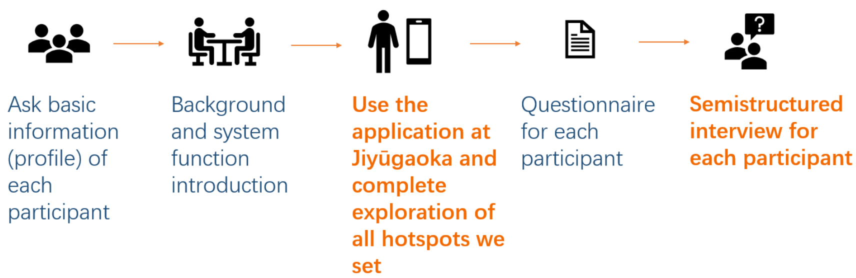


Figure 18 The progress of user study.

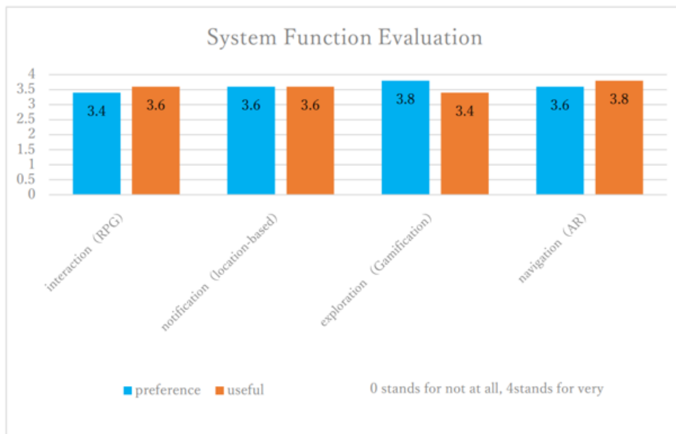


Figure 19 The result of the system function evaluation.

Regarding the system function evaluation, we asked the participants to answer the following 10 questions where answers range from 0 for not at all to 4 for very. Participants were asked whether they liked the function and whether they thought it was useful or not. The results are shown in Figure 19.

Regarding the experience satisfaction evaluation of the system, we asked participants to complete the following 8 questions, as illustrated in Table 3, where answers range from 0 for not at all to 4 for very. Five participants were also invited to participate in a semi-structured interview. The interview asked participants to describe their experience and provide some suggestions on the functions of the system. The results of the experience and satisfaction evaluation are shown in Figure 20. The interview results are also shown in Table 4.

Table 3 Questionnaire for experience satisfaction evaluation.

Q1. Do you think the system is useful?
Q2. Do you like using this system?
Q3. Did you enjoy the experience?
Q4. Were you interested?
Q5. Were you impressed?
Q6. Were you attracted to the system?
Q7. Do you think these functions can meet your demands?
Q8. If it is perfect enough, would you like to use the system in the future?

Figure 20 The results of the experience and satisfaction evaluation.

Table 4 Comments of the participants in interview.

Participants	Comments
P1	"I think this is a very interesting design. I was attracted by gamification contents. It can help me explore unknown destination, and sometimes I can get unexpected surprises. If it is to be used in real, I hope it can be more intelligent， which could understand context both my mental and physical condition, and provide me with a more comfortable service in a time…"
P2	"if there are several customized route plans for me to choose when I first arrived…I hope to use the least time to explore the most attractions"
P3	"maybe the group of people who used the app should be classified…travel destination as well…"
P4	"more travel mode for choose is better for me, such as weather, mood and so on…and the information. and virtual character should be more accurate…"
P5	"personalized service and interaction with other traveler maybe more interesting activity.."

4.3.3 Discussion

From the results, we learned that most of the participants thought the functions of the system were useful (average value=3.6) and liked to use this system to support their exploration demands (average value=3.8). Most of the participants considered our system interesting, reaching an average value of 3.8. Some comments from the interview were as follows: "I think this is a very interesting design. I was attracted by the gamification mechanism, which let me engage in exploring POIs one by one…" (P1). "It is helpful for me to explore interesting places by accident without the pre-plan in advanced" (P5). "The proposal notification from the virtual character makes me feel accompanied even if I explore the city blocks alone…" (P2).

According to these results, we learned that many of the participants thought this system enhanced interest in the entire exploration process. All the participants said that using this gamified navigation to explore destinations is more interesting than the traditional navigation or city guide applications they have used. Some participants believe that following the system's storyline to explore the attractions will help them generate complete and continuous memories. In addition, the interactive casual game tasks between the user and the real environment made participants feel more connected with the destination. Furthermore, this type of interactive system based on location can not only help pedestrians have better experiences but can also drive the commercial prosperity of city blocks. For example, we can extend the interaction function to the reality of business or with other residents and stores. We also found that the motivation and demands of participants were diverse. Some participants look forward to all kinds of navigation routes for them to choose.

We also found that some participants were unwilling to hold smartphones all the time during navigation and exploration. Therefore, providing diverse multimode interactions for exploration navigation is a valuable issue in the future. Based on our study results, we suggest some insights for location-based service and navigation design in city exploration. First, exploratory navigation routes should be diverse depending on different pedestrian preferences. Second, the exploratory navigation system needs to be more intelligent such as by possessing a context-aware ability, which could respond to changes in the environment. Then, multimode interaction should be considered to make navigation more comfortable and practical. Finally, more than one participant mentioned that they were concerned about safety and privacy when using this kind of system in city blocks, which are also challenges we need to solve in the future.

4.4 Answer to research question 1 and conclusion

This case study aims to investigate the interaction expectation of pedestrians via immersive technologies to support exploratory navigation. To better answer the research question 1: What are the pedestrians' needs and preferences for virtual interfaces in urban exploration? We investigate the user requirements to consider the different interaction expectations with the interface components during exploration. We implemented two exploratory navigation systems, a desktop virtual tour and a mobile AR navigation. Both systems combined gamified location-based interaction with navigation interface features. In the experiment, we asked different groups of participants to have a free-walking exploration in an assigned area of the urban streets via the system respectively. Based on our results, the interesting interaction between pedestrians and the navigation could help them acquire much more information and engage them in exploration. Moreover, we summarized the interaction requirements and preferences between the pedestrian and navigation interface. We found that the preference for different interface components is dynamic according to different scenario conditions.

In study 1, we expect to explore the interaction expectation with the virtual content from the participants through a virtual city tour. We found that both accurate navigation and unaided interest-based exploratory navigation are required. Moreover, the participants prefer receiving location-based information in an interesting way. In study 2, we combined gamification with mobile augmented reality navigation to explore pedestrian engagement through immersive interface of navigation guidance. We designed conventional wayfinding navigation with a gamified location-based POI notification. Based on our user studies, we summarized the interaction expectations during exploratory navigation and proposed design insights of the gamification mechanism for exploratory navigation to engage pedestrians in exploration.

Based on the results of the experiment, we found that participants show positive attitudes to navigation that embedded by XR technologies. Therefore, we can answer the first research question by suggesting design consideration for interface design for exploratory navigation. The motivation and needs of participants were complicated and dynamic. Both wayfinding and exploration are needed during exploratory navigation. The map interface doesn't need to exist all the time. Different map modes and interactions are expected. Different POI visualization methods are required according to the different conditions of the scenario. User requirements for interaction with the real world and virtual content in exploration are different. The interaction between the pedestrian and virtual content should not be isolated to the opposite. It should relate to the physical world. The results indicate that the interface of the mixed reality navigation via HMDs should be designed dynamically and provide pedestrian both the spatial information and the location-based POI information. Therefore, in this work, we plan to discuss these two aspects in detail respectively.

Figure 21 shows two aspects design consideration for interface design of mixed reality navigation via HMDs. The results of case study 1 also indicate that the interaction between the three objects, users, virtual interface and the real-world should be discussed between every two objects. Moreover, the Figure 22 shows the interaction between each object is impact by the map interface design and POI visualization methods.

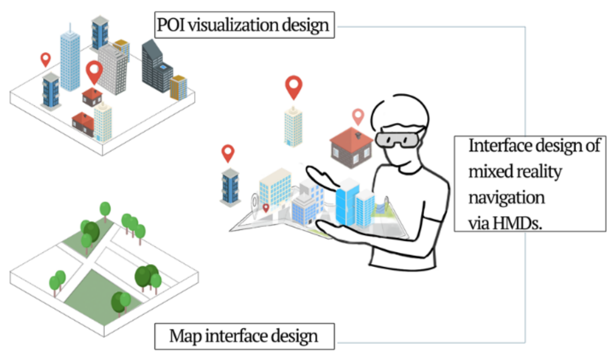


Figure 21 Two aspects design consideration for interface design of mixed reality navigation via HMDs.

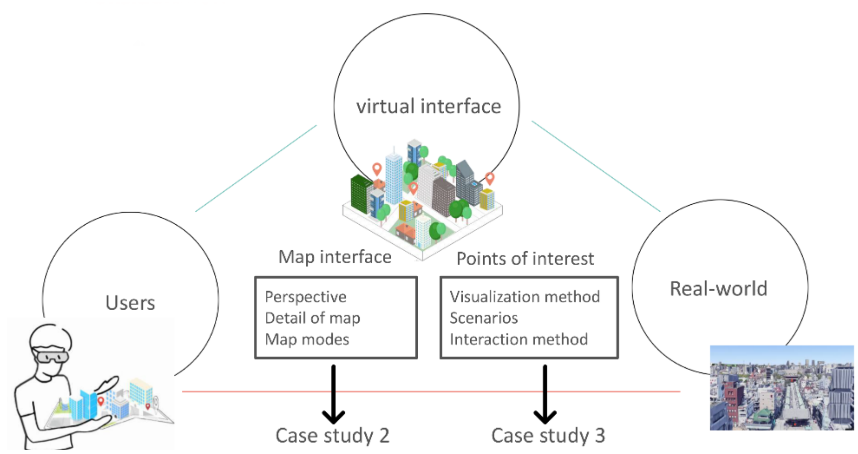


Figure 22 Three objects in exploratory navigation and the interaction between each object is impact by the map interface design and POI visualization.

Chapter 5 Case study: virtual map design for promoting urban exploration

This chapter is written based on the part of the section in the journal paper [74].

In this case study, we aim to explore the role of the virtual map interface of mixed reality HMD navigation on pedestrian satisfaction. First, we proposed a virtual 3D minimap. Then, to further discuss the effect of the level of detail of the minimap interface on pedestrian satisfaction in exploratory navigation, we designed two levels of detail of map modes to investigate the suitable map interface design.

5.1 Introduction

In this work, we propose a mixed reality 3D minimap as a part of the navigation interface through the mobile head-mounted display to support urban exploratory navigation. We hope the proposed map interface will provide pedestrians with a holistic view of spatial and environmental information and increase interactivity with the virtual contents rather than just displaying the virtual marks through hand-held augmented reality navigation. We devoted ourselves to exploring the role of the virtual 3D map in future mixed reality navigation, which aims to enhance pedestrians' mental satisfaction in urban navigation. To further discuss the effect of the level of detail of the minimap interface on pedestrian satisfaction, we designed two levels of detail for map modes: a normal one with complete spatial and environmental information and a simplified one that filters the irrelevant information.

According to the literature review of related works, we found that mental satisfaction in pedestrian navigation is affected by various attributes and should be measured comprehensively. In this work, we utilized three factors to measure the mental satisfaction of pedestrians in exploratory navigation: performance in exploratory navigation, NASA-TLX workload, and user experience. Thus, we investigated which map mode we designed is most suitable and can enhance pedestrians' mental satisfaction. To better answer RQ2: What is the role of the virtual map as the part of mixed reality navigation interface during urban exploration? And how can we design a suitable map interface to promote urban exploration? we divided the research questions as follows:

• RQ2-1: Which map mode can result in a better performance in exploratory navigation?

• RQ2-2: Which map mode can result in a lower perceived workload in exploratory

navigation?

• RQ2-3: Which map mode can result in a better user experience in exploratory navigation?

5.2 Mixed reality3D minimap design

In this section, we introduce the design concept of the 3D minimap interface we proposed and describe the implementation. The proposed map interface aims to assist pedestrians in exploring a specific destination area in an urban environment. It was designed as an interactable virtual 3D minimap (like a virtual 3D sandbox in one's hands). Like the paper map held in hands, pedestrians can hold the virtual 3D minimap, which is displayed by a mixed reality head-mounted display, and manipulate it through two hands to locate objects, learn POI information, explore, and navigate at any time. In Figure 19, we illustrate different map interfaces in different devices: paper maps (Figure 23-(A)), digital maps in smartphones (Figure 23-(B)), and mixed-reality 3D minimap (Figure 23-(C)) designs. The mixed reality 3D minimap could be considered to combine the advantages of paper maps and digital maps in smartphones.

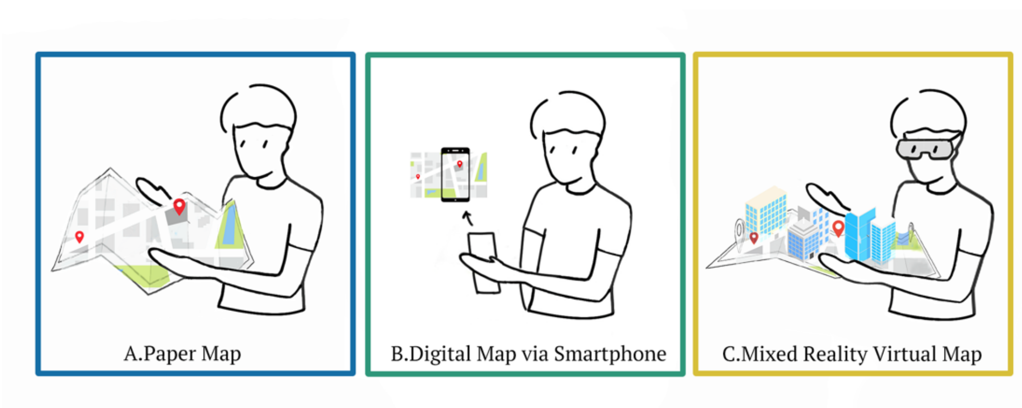


Figure 23 Illustration of three different navigation map modes. (A) illustrates the conventional paper maps. (B) illustrates the digital maps via a smartphone. (C) illustrates the mixed reality 3D minimap via a mobile mixed reality head-mounted display.

5.2.1 Interface component

Our method is inspired by the minimap mechanism in video games which aims to help players orientate and locate themselves and grasp their environment and targets efficiently and comprehensively. There are studies on the minimap being applied in navigation [75-77] to help players to walk and explore. Thus, we expect the design of the minimap mechanism could also be applied in the future exploratory navigation system. Unlike traditional 2D orthographic minimap in video games, our mixed reality 3D minimap presents 3D spatial and environmental information in a bird's-eye view, and pedestrians can manipulate the map by zooming, rotating, and transforming.

As shown in Figure 24, the mixed reality 3D minimap consists of three layers: a base map layer, a feature layer, and a layer of controls. In the base map layer, the spatial and environmental information of geographic features, such as continents, lakes, administrative boundaries, streets, cities, and place names, are presented to depict the essential components of a map base. In the feature layer, detailed information of a grouping of similar geographic features exists, such as POI of landmarks, buildings, and roads. Finally, the control layer includes the interaction between pedestrian and map layers.

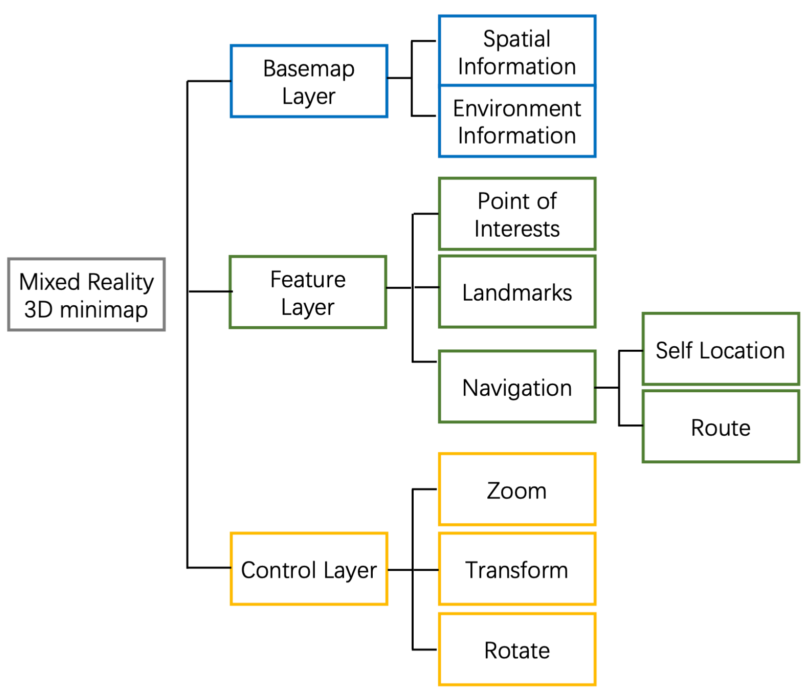


Figure 24 User interface model.

➢ Point of interest (POI) and landmark

POIS are marked in the feature layer of the minimap interface to support exploration. Like the conventional map, which is applied daily, we set a series of virtual marks to illustrate the POIs and landmarks in a 3D minimap interface. Three kinds of POI labels were designed to represent restaurants and foods, attractions and landmarks, and stores for shopping. The pedestrian could refer to the POI information in the map interface to decide if they would like to arrive and explore the POI in which they might be interested. Figure 25 shows the visualization of POIs in the 3D minimap demo used in the user study.

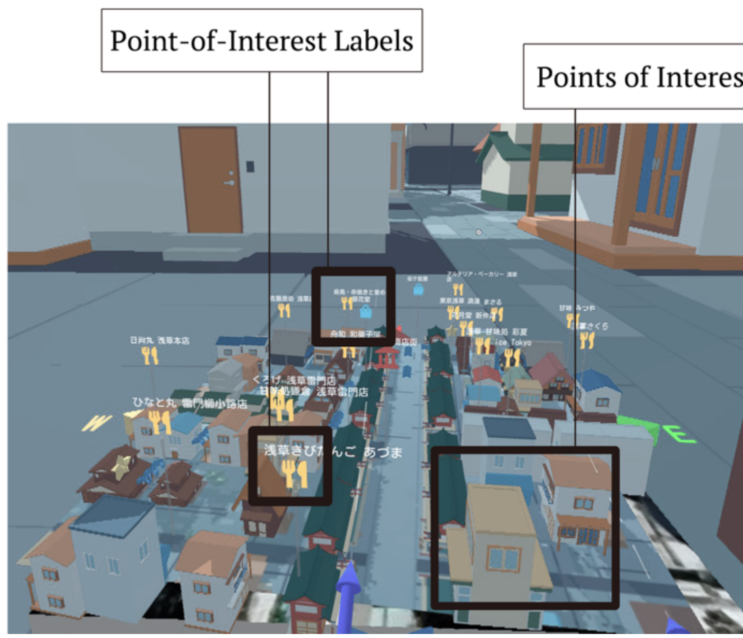


Figure 25 Visualization of POIs in 3D minimap demo used in user study experiment.

➢ Navigation

In this work, we hope pedestrians could only refer to 3D minimap to navigate without route instructions on some occasions. We summarized the different needs during exploratory navigation and found that pedestrians may not always need precise navigation, and sometimes they just follow a rough direction according to the map. Therefore, we hope to explore whether the 3D minimap could help pedestrians recognize the spatial distribution and navigate from one original point to a destination point without route turn-by-turn instruction to avoid being over-controlled by the navigation during exploration.

In our method, the navigation in feature layers is split into two mechanisms. With the first navigation mechanism, we hope pedestrians can explore by referring to the 3D minimap with the self-location component, like using a digital “Where I am map” to orientate and navigate. On the other hand, for the second mechanism, the pedestrian could follow route instructions displayed as a series of virtual arrows from the origin to the destination point. Figure 26 shows navigation features in the map interface.

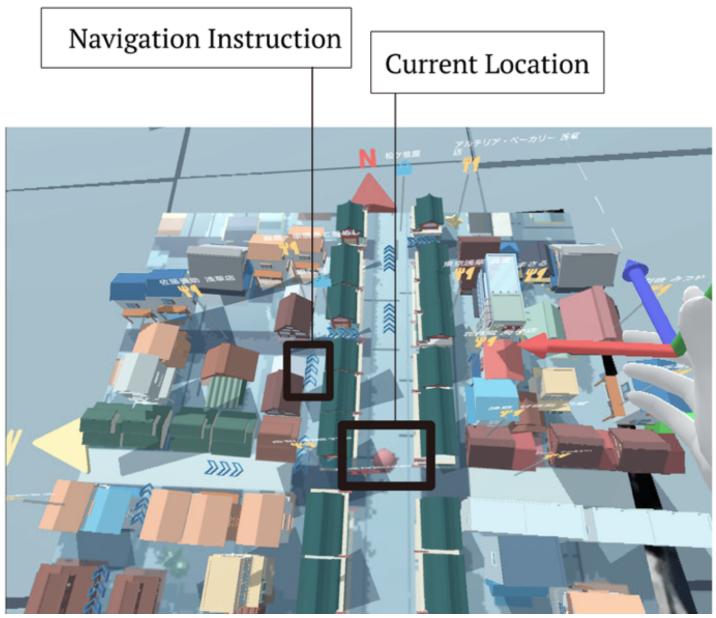


Figure 26 Navigation features in map interface.

- Layer of control

In an ideal situation, the virtual 3D minimap is projected via a head-mounted display, and it could be operated with two hands of a pedestrian, like using a virtual sandbox with two hands, which is different from the interactions with a conventional map interface on a mobile device. The control mechanism in this work focuses on the zoom, transform, and rotate to change the map size range, location, and direction to support exploration. In detail, the pedestrian could refer to the map while walking and exploring. The map was designed to transform along with the movement of the pedestrian’s location.

5.2.2 Two different levels of detail map design

To explore and discuss the impacts that result from the different levels of detail of the map interface, we further propose both the normal and the simplified 3D minimap modes. We aimed to use different detailed map modes to investigate the suitable interface in exploratory navigation. Firstly, we conducted a preliminary study as the first phase of this work. Then, based on the literature and the preliminary interview results, we designed the simplified map mode in detail to further explore the impacts of different levels of detail maps.

5.2.2.1 Preliminary study

To investigate the pedestrian's needs for the map interfaces with different levels of detail, we first conducted a field study with 5 participants (4 females, average age = 27 years, SD = 2.54) as a preliminary study in a real street block of the urban environment.

We designed a free exploration task with augmented reality navigation in an assigned urban area. A series of landmarks were marked on the map to assist pedestrians with searching and browsing in the surrounding area. Like the Google Maps we use daily, we designed the default map interface with 2D, and 3D default map modes and the 3D aerial map mode generated by global satellites. For the augmented reality function, participants could use augmented reality features to find the POI following the virtual anchor in the augmented reality interface corresponding to GPS information. A map view window with three different maps was added as a part of the interface to assist participants in exploration. The participant could switch among three map mode interfaces according to their preferences and need. The system prototype was developed by Xcode [78], and the map and augmented reality features are supported by MapKit [79] and ARKit [80]. The application used in the experiment was installed on an iPhone 7 with the iOS 13.5 system. Figure 27 illustrates the prototype we used in the experiment.

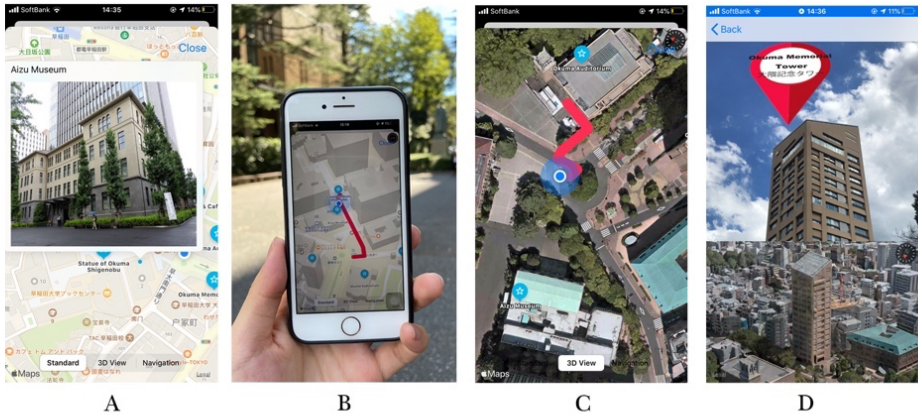


Figure 27 Prototype screenshot of the different mode navigation interfaces.

From the interview results shown in Figure 28, we found that the participants showed different preferences for the three map modes during the exploration task according to their different needs. Some participants mentioned that they preferred using the 3D aerial map to identify the appearances of landmarks, POI, and other buildings, which could help them orientate and locate in rough directions instead of using explicit navigation. However, some participants also mentioned some deficiencies when referring to the 3D aerial map in some cases. For instance, sometimes they do not need such detailed, complicated information.

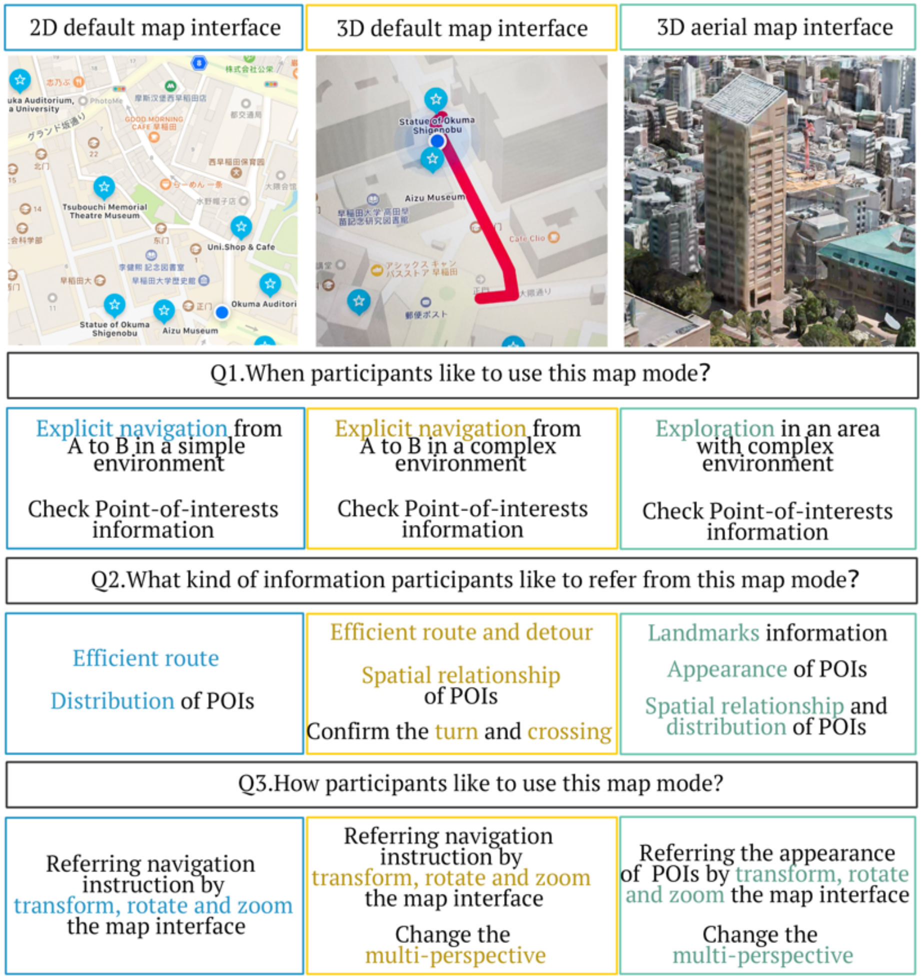


Figure 28 Preliminary study results.

Moreover, some participants said that the POI information was sometimes overloaded in the augmented reality interface, which affected the navigation experience. For instance, some participants mentioned that they prefer more valuable POIs for exploration rather than presenting all the POIs on the map interface. Based on the preliminary study results, we can learn that when pedestrians walk and explore in an urban area, they prefer following the landmarks with impressed appearances to navigate in a rough direction.

5.2.2.2 Method for simplified map design

Based on the preliminary study, in Figure 26 we illustrate the designs of different levels of detail in the normal 3D map mode and the simplified 3D map mode.

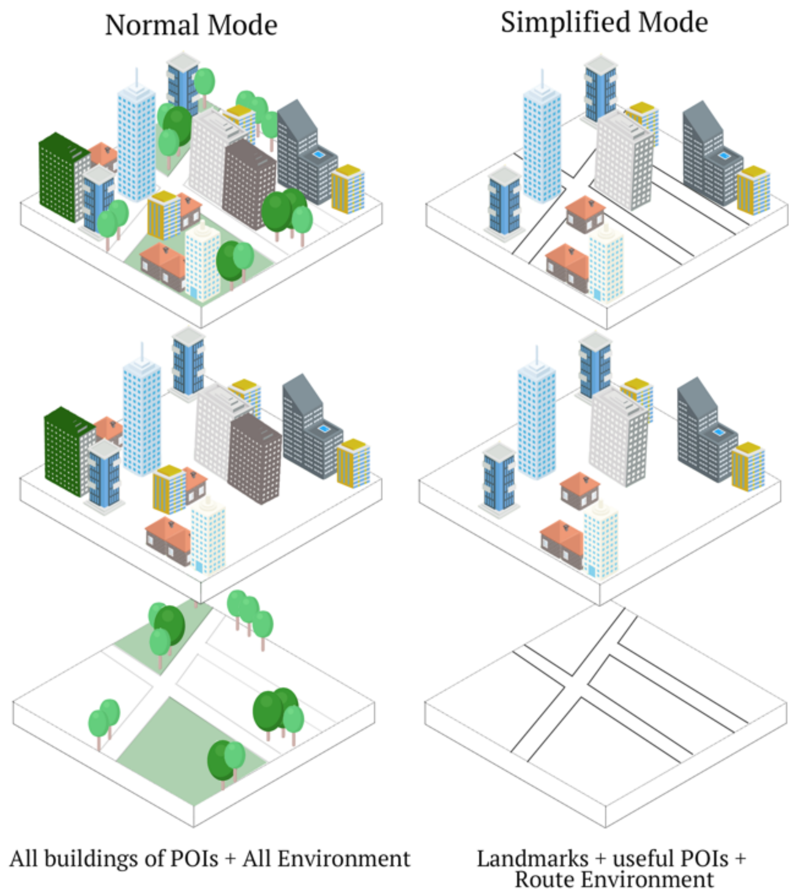


Figure 29 Left: normal mixed reality 3D minimap design; Right: simplified mixed reality 3D minimap design.

As the Figure 29 shows, we simplified the map interface from the base map and feature layers to reduce the complexity, which results from the over-realistic information from the normal 3D map. The normal map consists of all the components of the base map layer and feature layers, which could be considered a mirrored map of the real world. However, as for the simplified one, we simplify the complicated spatial and environmental information in the base map layer. As for the feature layer in simplified map mode, the valuable POIs, for instance, restaurants and foods, attractions and landmarks, and stores for shopping are retained, and the private buildings, POIs not for visiting and exploration, are filtered out. It is noted that the filtered information in simplified map mode is represented in 2D map mode. We expect that the simplified 3D minimap can emphasize vital information, which can assist pedestrians in exploring and navigating.

In the experiment section later, we introduce the design of these two modes during exploratory navigation to discuss the suitable level of detail of the 3D minimap for future usage.

5.3 Experiment

5.3.1 Experiment design

We aimed to utilize virtual reality to simulate outdoor mixed reality navigation through mobile head-mounted displays, such as HoloLens, in real-world scenarios. To better control irrelevant variables in the experiment and to face the risk of outdoor activity resulting from COVID-19, in this work, we planned to use a virtual reality environment to simulate the mixed reality scenario to conduct a user study. Moreover, the research on mixed reality 3D minimap design for exploratory navigation is not rich in the literature, and we expect this study will become an inspiration for further study as well. The design of 3D minimap in this work is still in the preliminary stage, so we could make use of the advantages of virtual reality, such as lower cost, variation control, and easier manipulation to conduct the user study for mixed reality applications, and we conducted a field study in the real world after studies in simulation. Utilizing the virtual reality method to simulate augmented reality and mixed reality study is common in research. The advantage of this method is reducing the cost of outdoor field experiments, and since it is easier to recognize the problems that the design should overcome during testing, it is worth experiencing the augmented reality and mixed reality prototype after virtual reality [81, 82]. There exists a lot of studies on utilize virtual environment to simulate navigation activities [83-86]. Figure 30 shows the design concept for participants in the virtual scene with a 3D minimap.

We implemented a virtual urban scene and used a virtual reality head-mounted display to simulate the mixed reality features. To discuss the exploratory navigation comprehensively, we designed two experimental tasks described in Figure 31. We designed the exploration task and navigation task to simulate the activities in urban exploratory navigation. After each task, the answers to the questionnaires and interviews were recorded. The virtual urban scene was implemented in Unity 3D. We used the open prefab models imported from the Unity Asset Store to implement the Senso-Ji in Tokyo as a virtual urban street environment, as illustrated in Figure 29.

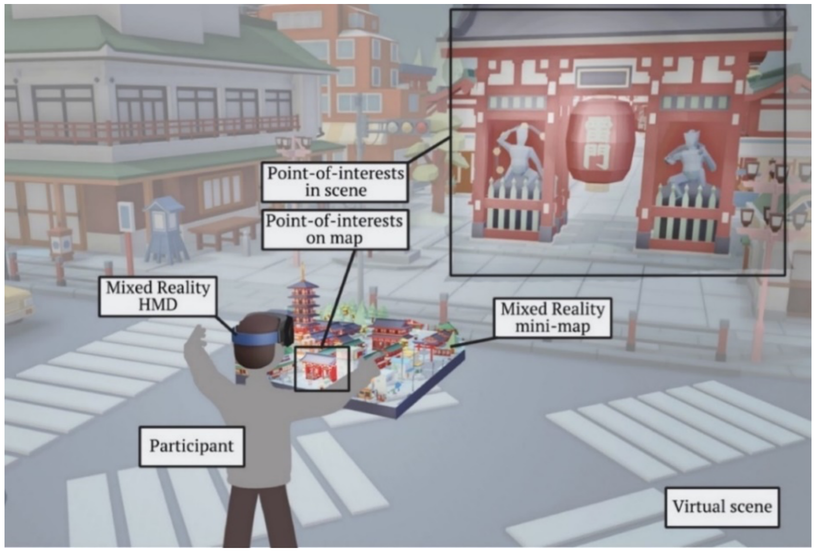


Figure 30 Implementation description.

	Experimental Design			
Tasks	Exploration Task		Navigation Task	
Scenarios Description	Normal Map	Simplified Map	Normal Map	Simplified Map
	Participant was asked to explore in a virtual city street area in an assigned time(6min). Participant was asked to arrive at POIs in virtual scene which are marked a star on the mini-map.		Participant was asked to navigate in a virtual city street area in an assigned route-planning. Participant was asked to arrive at POIs in virtual scene referring to mini-map route instruction.	
Task Phases	**1**.Practice Mode for VR operation		**1**.Practice Mode for VR operation	
	2.Start exploring via **normal** MR mini-map from a random point.	**2**.Start exploring via **simplified** MR mini-map from a random point.	**2**.Start **route1** navigaton via **normal** MR mini-map.	**2**.Start **route2** navigation via **simplified** MR mini-map.
	3.When participant approaching the star marked POI, a 3D virtual star will be triggered and appear at the POI location which partici--pant could collect the star. **4**.When time is up, the number of collected star will be recorded. **5**.Anwser the questionnaire.		**3**.Participant will be instructed by mini-map route-planning from start to destination point. **4**.When participant arrive at the destination, the time of navigation will be recorded. **5**.Participant will be asked to depict the route. **6**.Anwser the questionnaire.	
Behavioral Measurement	Collected POIs number		Navigation time(s), Route drawing	
Subjective Measurement	NASA-TLX, Experience questionnaire		NASA-TLX, Experience questionnaire	

Figure 31 Experimental design.

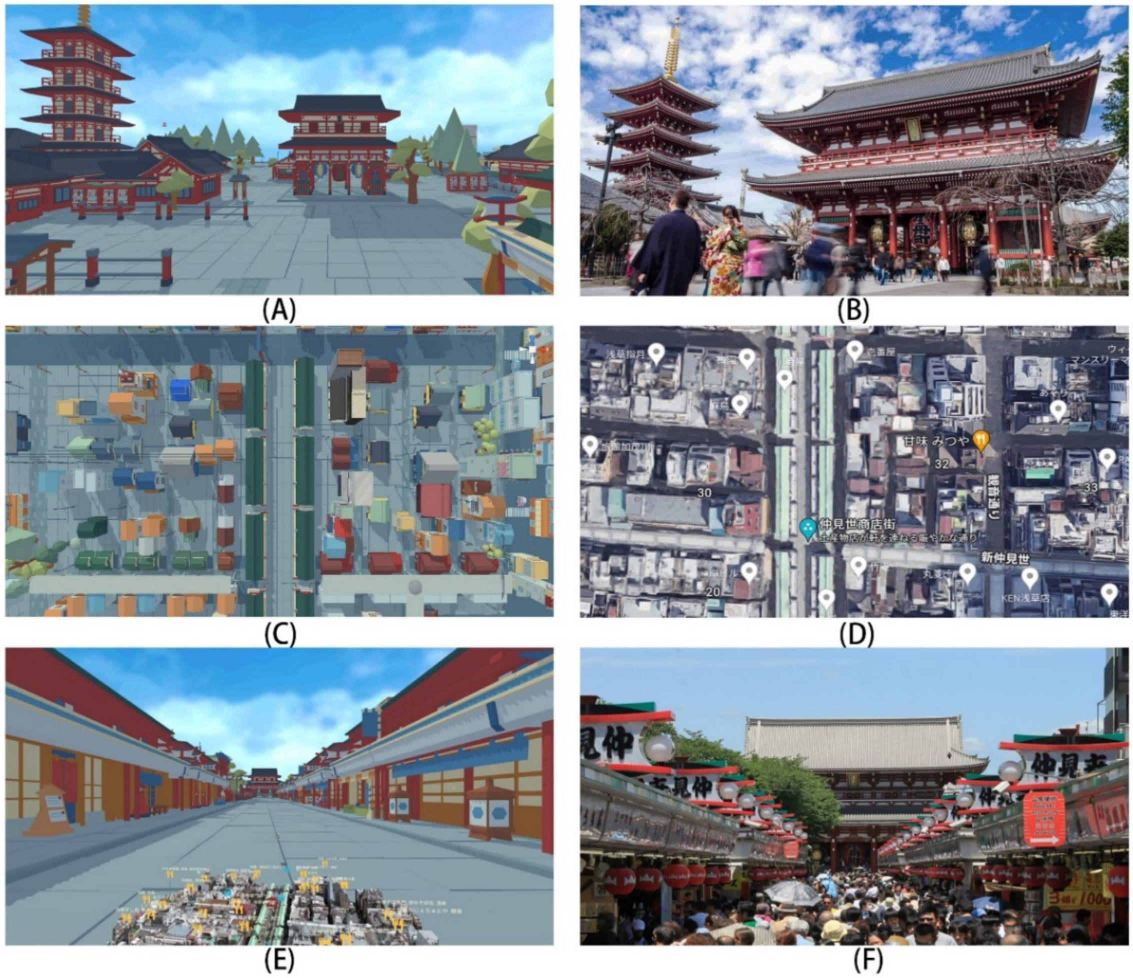


Figure 32 This figure shows the virtual urban scene we implemented for user study, Senso-Ji Temple in Tokyo, Japan.

Figure 32-A and B show the famous sightseeing in Senso-Ji in our virtual scene and the rea world respectively.

Figure 32-C shows overall view of Senso-Ji with various POIs.

Figure 32-D shows the distribution of various POIs captured from Google Map.

Figure 32-E shows the Nakamise shopping street in Senso-Ji in virtual scene with a 3D realistic map marked with numerous POIs.

Figure 32-F shows the real-world photo of Nakamise shopping street with a lot of visitors.

Many tourists, both Japanese and from abroad, visit the Senso-Ji Temple every day. The area surrounding the ancient sightseeing has many traditional shops and eating places that feature traditional Japanese dishes. These shops represent part of a historic and existing tradition of selling to pilgrims who made the journey to Senso-Ji. In our virtual scene, we included detailed buildings, landmarks, streets, plants, facilities, and other environmental information according to the real-world distribution of Senso-Ji. We used Oculus Quest 2 [87] to conduct virtual reality experiment to simulate the mixed reality outdoor activities.

In the exploration task, we aimed to measure the performance in terms of the collected POIs, perceived workload, and user experience in the two map modes. The participant was asked to explore an urban street area. We set a series of POIs in the virtual scene and marked these POIs in the minimap interface as well. The participants were asked to explore and arrive at these POIs in the virtual scene according to the minimap. This task aimed to simulate exploration activities such as check-in behavior in a tourism destination. In another task, the participant needed to utilize the virtual minimap for orientation and navigation to collect stars within a session. We also implemented a scoring system to record the number of collected POI. The starting points and the series of marked POI locations in the two map modes were designed differently to avoid an influence on the latter experiment resulting from the former one. We measured the number of collected POIs as quantitative data, and we used the subjective questionnaire NASA-TLX and game user experience questionnaire as qualitative data for later analysis and discussion.

In the navigation task, we aimed to measure the navigation efficiency (navigation time(s)), perceived workload, and user experience in the two map modes. To avoid the spatial memory of the first map mode task affecting the second one, the starting points and destinations in the two modes' minimap tasks were different, but the distance and the route complexity of the two map modes' navigation tasks were the same. The participant was asked to navigate from the starting point to the destination location following the route instruction display on the minimap interface. This task was designed to simulate precise wayfinding navigation activity during exploration. We recorded the navigation time and asked for route descriptions from the participants in two modes, and we used the subjective questionnaire NASA-TLX and the user experience questionnaire as qualitative data for analysis and discussion.

5.3.2 Participants

We recruited 28 participants (10 females, 18 males) and divided them into two groups for different tasks (14 participants in each group). The average age was 25 years; the range was 22–29 years. Most of them (93%) liked exploring POIs in urban streets in daily life. Only 21% of the participants had the virtual reality experience with a headset. All the participants were given a detailed description of the research and a full explanation of the user study procedure. We also asked them to approve the information used in this study.

5.3.3 Experimental procedure

First, we gave each participant a detailed introduction to the whole study and experimental procedure. After obtaining personal information and informed consent, each participant was made to practice the operation via Oculus Quest 2 in the virtual reality scene. They were taught to use two controllers to move in the scene and operate the minimap. Then, when the participant was familiar with the motion control in the virtual reality scene, we instructed him to start the tasks according to the experimental design. The behavioral measurement and subjective measurements were recorded after each task. Moreover, we also asked each participant several questions about their preferences and attitudes toward minimap utilization as a semi-structured interview. All the quantitative data we obtained were analyzed through a non-parametric Wilcoxon signed-rank test [88] at the 0.05 significance level. Figure 33 shows some participants involved in the task, and Figure 34 shows some scenes with minimap interfaces during the experimental task.

Figure 33 Some participants in the task.

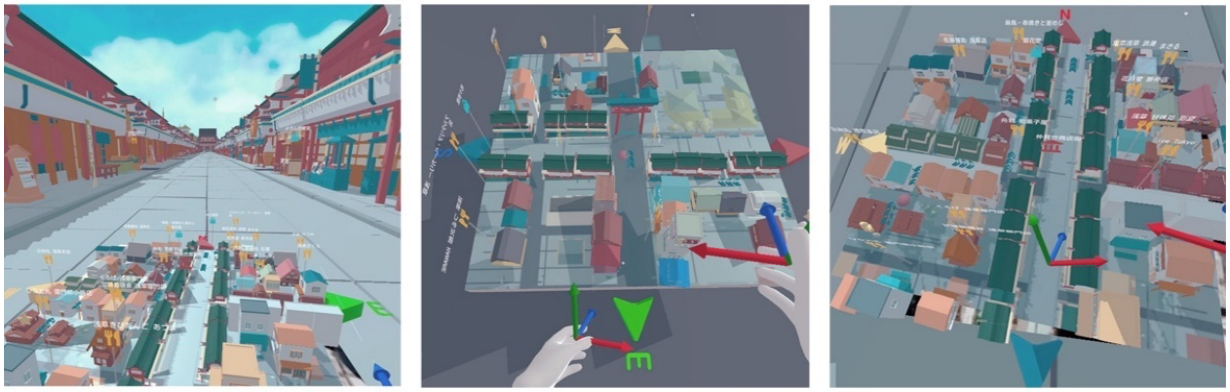


Figure 34 Virtual scenes and minimap interfaces in the task.

5.4 Results

5.4.1 Quantitative results

- Result of exploration task

  Figures 35–37 show the behavioral and subjective measurement results of the exploration task.

Figure 35 shows the number of POIs collected in the exploration task. The number of collected POIs was significantly ($p < 0.005$) higher in the simplified mode. The results mean that the participants could arrive at and collect much more POIs via the simplified-mode virtual minimap. As for the results of the interview, we found that participants also mentioned that the simplified mode could help them navigate the POIs efficiently, so they could perform better in collecting the POIs in the simplified mode.

The NASA-TLX trial was conducted immediately after completing each exploration trial, and the overall scores and every independent component score were calculated. In Figure 36, we can see the mean values of overall NASA-TLX scores. Additionally, we can see that participants rated their overall workload scores significantly ($p < 0.005$) lower in the simplified mode, which indicates that the simplified mode in this work resulted in a lower overall workload score in the exploration task than in the normal mode. However, as for the mean values of independent component scores in the two map modes in Figure 37, we can see that participants only rated the mental demand score of the simplified mode statistically significantly ($p < 0.05$) lower than that of the normal mode. Although the mean values of all the other independent component scores are lower in simplified mode than in normal mode, the differences are insignificant (p > 0.05). The results mean that the simplified map mode resulted in a lower overall workload and mental demand in the exploration task.

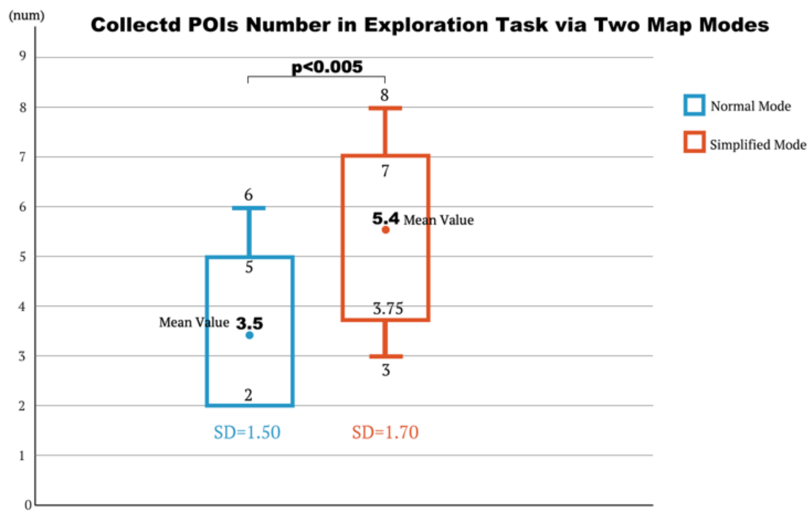


Figure 35 Box plot of collected POIs in an exploration task with two map modes.

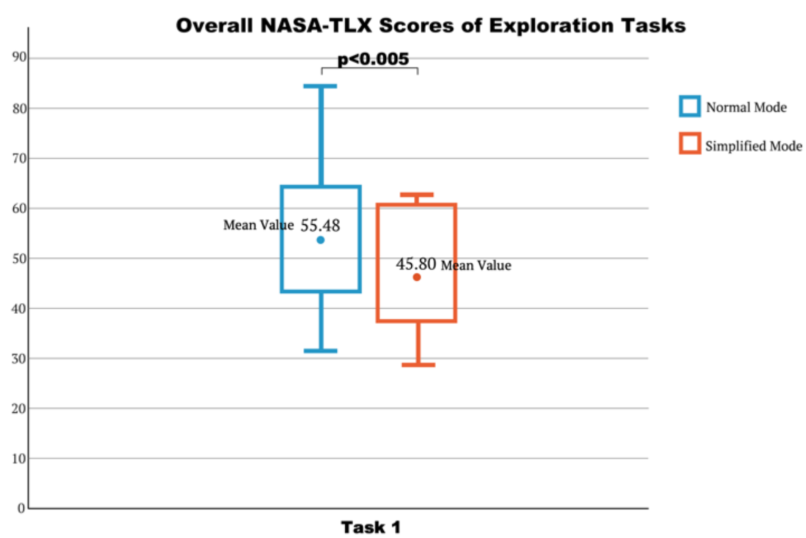


Figure 36 Box plot of overall workload scores in an exploration task with two map modes.

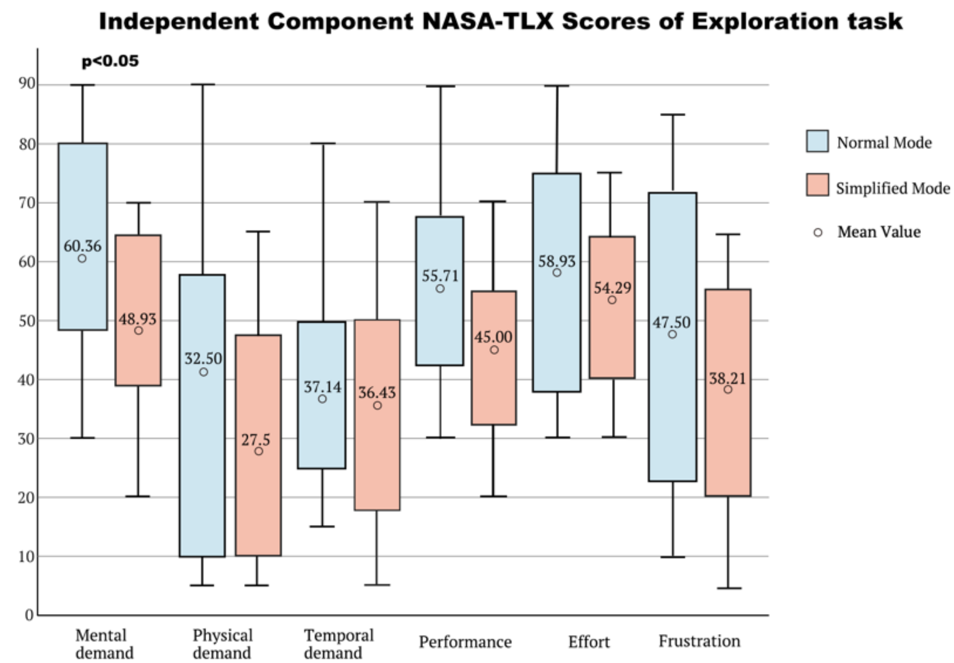


Figure 37 Box plot of scores of each independent component of NASA-TLX with two map modes.

- Result of navigation task

  Figures 38–40 show the behavioral and subjective measurement results of the navigation task.

As shown in Figure 38, in the navigation task, the navigation time in the normal mode was significantly ($p < 0.01$) higher than in the simplified mode, which means that the simplified mode could assist participants in finding destinations more efficiently, so the participants performed better in simplified mode.

The NASA-TLX trial was conducted immediately after completing each navigation trial. In Figure 39, we can see that the mean value of the overall workload score was significantly ($p < 0.05$) lower in the simplified mode, and from Figure 40, we can see that participants rated scores of the mental demand and effort independent component significantly lower ($p < 0.05$) for the simplified mode than the normal mode. The results mean that the simplified map mode resulted in a lower overall workload, mental demand, and effort demand in the navigation task.

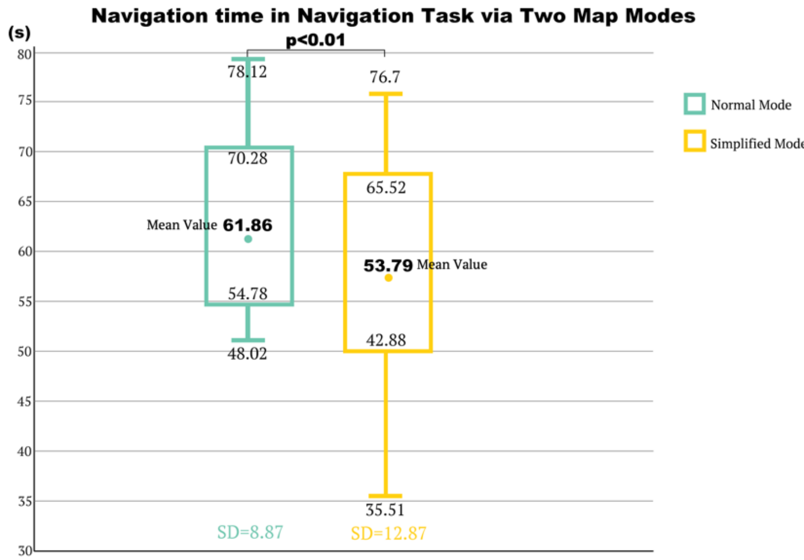


Figure 38 Box plot of navigation times in the navigation task with two map modes.

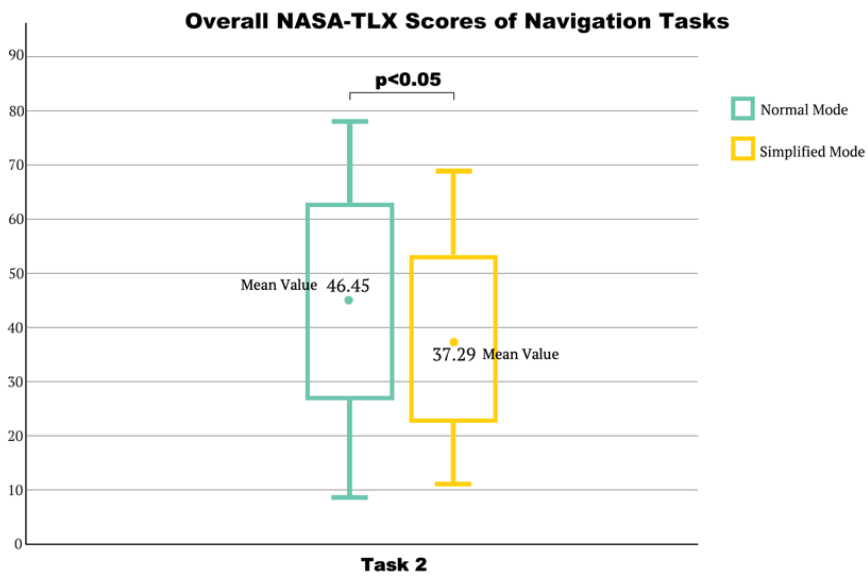


Figure 39 Box plot of overall workload scores in the navigation task with two map modes.

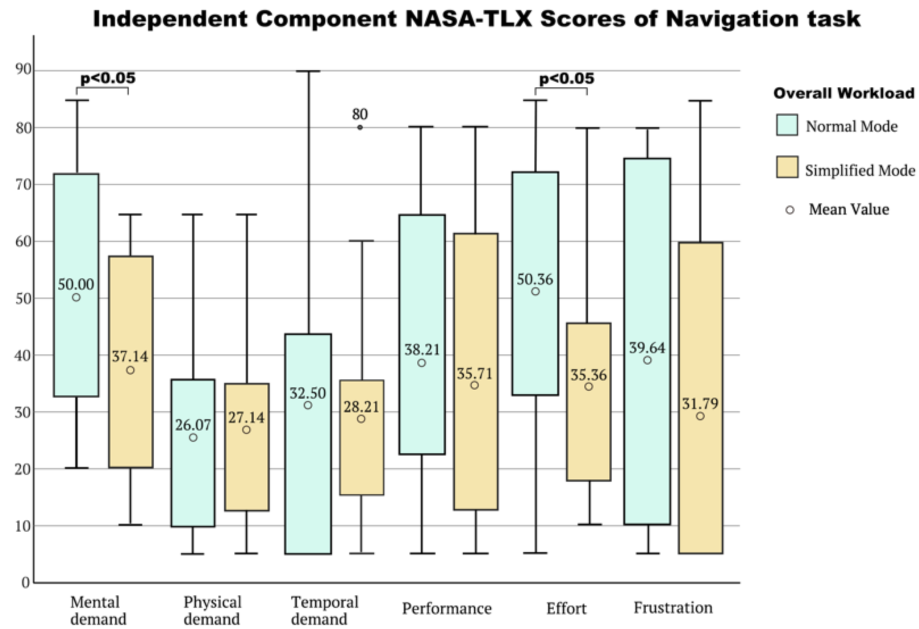


Figure 40 Box plot of scores of each independent component of NASA-TLX with two map modes.

5.4.2 Qualitative results

The overall user experience preferences can be seen in Figures 41–43. In the exploration task, we used the game user experience questionnaire (GUEQ) to measure the participants' preferences because we considered that the exploratory navigation is more like the exploratory game. Therefore, we selected four questions with a 5-scale questionnaire related to positive exploration experience and four with a 5-scale questionnaire related to the negative experience. All the questions are illustrated in Figures 41 and 42. In brief, we can know from the figure that the preference of each question according to positive game user experience questions was rated higher in simplified mode than in normal mode.

As for the negative game user experience items, we can see that the participants gave lower scores for the simplified mode, meaning the negative experience during exploration was lighter than in the normal mode.

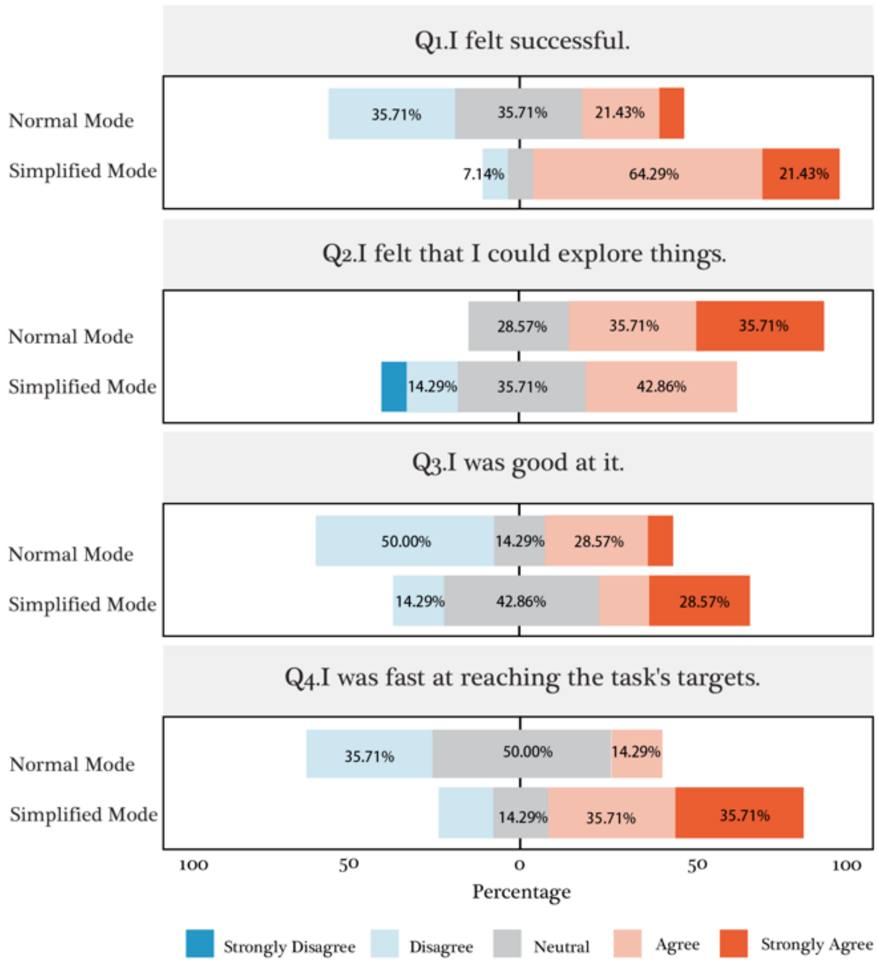


Figure 41 User preferences on positive questions of GUEQ in the exploration task.

We used four questions from the user experience questionnaire (UEQ) to evaluate the participants' preferences in the navigation task. The mean value of each item rated in the 7-scale questionnaire is illustrated in Figure 43. The overall preference of users in navigation tasks was for the simplified mode.

In the semi-structured interview of the user preference questionnaire, we asked every participant when and where they preferred to use each mode of the minimap. The answers are summarized in Figure 44.

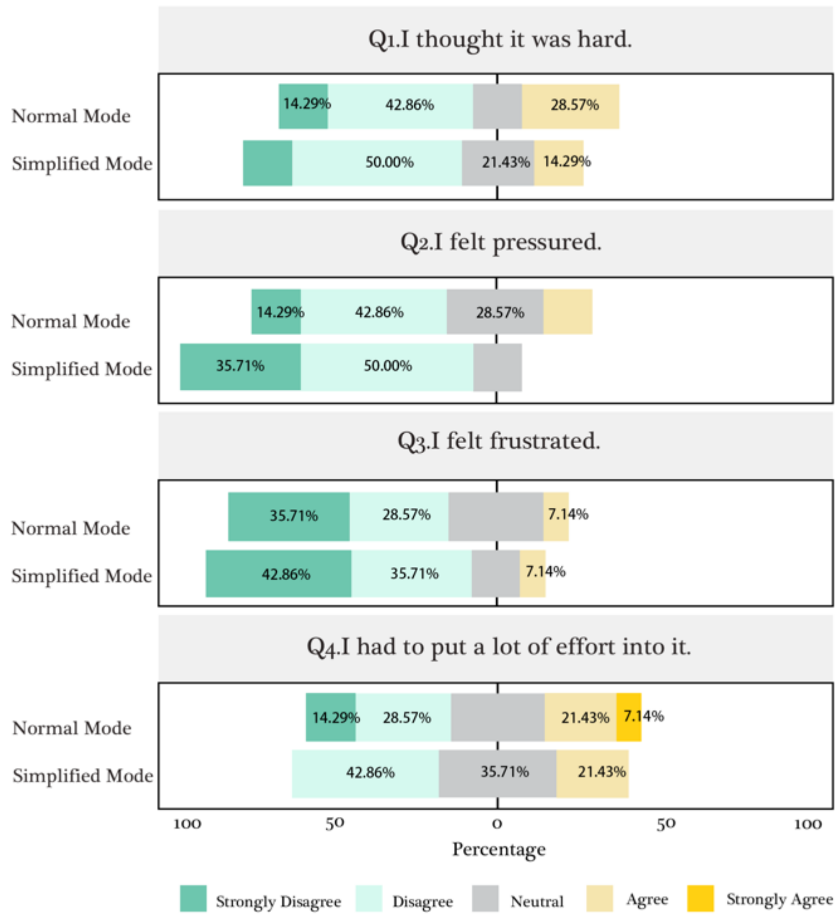


Figure 42 User preferences based on negative questions of GUEQ in exploration task.

Based on the user experience questionnaire and interview results, most participants showed a preference and positive attitudes toward the simplified 3D minimap, which could assist them in completing the tasks. For example, participant 4 said he preferred to use the simplified mode to assist with locating places in a complex urban context without using turn-by-turn navigation instructions sometimes. Additionally, participant 6 gave a scenario in which she preferred using a simplified 3D minimap to find a specific destination with a rough direction without navigation instructions because she did not want to miss any POI by being over-controlled by the navigation system.

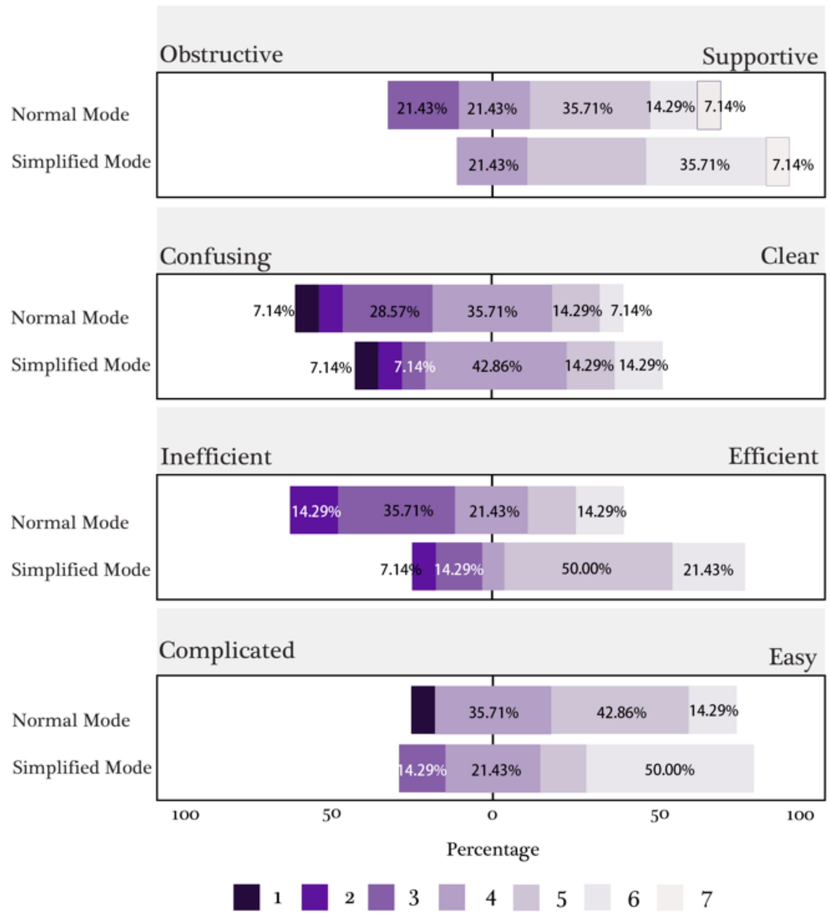


Figure 43 User preferences based on selected questions of UEQ in navigation task.

Semi-structure interview	Normal MR 3D mini-map	Simplified MR 3D mini-map
When would you like to use this mode mini-map?	Participants prefer using normal 3D mini-map when they want to acquire accurate information, like explicit route and location information . Participants prefer using normal 3D mini-map when they want to grasp the holistic distribution of POIs Participants prefer using normal 3D mini-map when they want to use realistic information to specify similar.buildings closer to them.	Participants prefer using simplified 3D mini-mapnwhen they want to acquire information roughly, like rough direction for roaming. Participants prefer using simplified 3D mini-map when they are have limited time for exploration. Participants prefer using simplified 3D mini-map when they want to navigate from one location to another destination to avoid overwhelmed environment information.
Where would you like to use this mode mini-map?	Participants prefer using normal 3D mini-map in an unfamiliar city street area for walking and exploration Participants prefer using normal 3D mini-map in theme park, forest park, etc.. Participants prefer using normal 3D mini-map under the ground to specify more detail information of location and POIs.	Participants prefer using simplified 3D mini-map in an unfamiliar city street area for walking and navigation. Participants prefer using simplified 3D mini-map in a complicated environment to found valuable POIs efficiently.

Figure 44 Semi-structured interview of user preference.

5.4.3 Discussion and conclusion

5.4.3.1 Performance in exploratory navigation

In this work, we used POI exploration and navigation of route planning to simulate different activities in exploratory navigation. Therefore, we designed two experimental tasks and utilized behavioral measurements to evaluate their performance in them. In the exploration task, we hope to assist pedestrians in exploring more POIs in the exploration task via our mixed reality 3D minimap. The results show that the mean value of the collected POIs in the simplified map mode experiment session was higher. The number of collected POIs was significantly ($p < 0.005$) higher via the simplified map. However, in the interview after the tasks, some participants mentioned that the difference between the normal mode and the simplified mode for browsing the valuable POIs was not big, and the significant difference in collected numbers probably resulted from the high efficiency during wayfinding in exploration tasks via the simplified map mode. We consider this to have been because the mixed reality 3D minimap could give participants a precise distribution of POIs from a bird's-eye view, making it easier to browse many POIs and improve the wayfinding efficiency in exploration tasks. This is also consistent with the results in the navigation task below.

In the navigation task, unlike the free walking and self-navigation in the exploration task, we set route navigation instructions for two locations. The results showed that the mean value of the navigation time via the simplified mode indicated more efficient navigation to a statistically significant degree ($p < 0.01$). We supposed that the simplified 3D minimap mode provided clearer route information related to landmarks, buildings, and other POIs. From the interviews, we also found that the participants thought the simplified 3D map mode was more efficient for orientating and locating, which helped them accomplish precise route navigation.

Based on the results of the two tasks, for Research Question 2-1, though the results in both tasks were significant, we cannot say that the simplified mixed reality 3D minimap mode can result in better performance in exploratory navigation. We could suppose that in this work, the simplified mixed reality 3D minimap mode could result in better efficiency in the specific navigation task. Therefore, we suggest the simplified method of the proposed 3D minimap needs to be further studied in more scenarios. For instance, we only discussed the difference between valuable and irrelevant POIs in this work. We believe the results will show different things in other simplified criteria in different scenarios. In addition, different navigation scenarios should be considered as well. For example, in our work, the simplified minimap improved the navigation efficiency in both exploration (self-location without turn-by-turn wayfinding instruction) and navigation (assigned turn-by-turn navigation) tasks. Thus, researchers can investigate interfaces that are suitable for different navigation methods in the future.

We supposed that based on our work, we could learn that the mixed reality minimap has the potential to assist pedestrians in specific scenarios, such as understanding the holistic spatial distribution and POI information from a bird's-eye view. However, whether these benefits are required all the time in all the urban exploratory navigation scenarios still needs to be discussed. For instance, the dynamic map interface might satisfy the different needs of pedestrians during urban exploration.

5.4.3.2 Perceived workload

For the NASA-TLX questionnaire results on perceived workload, we found that in both tasks, the overall workload score via the simplified 3D landmark-based minimap was significantly ($p < 0.05$) lower than that of the normal 3D minimap. However, for the independent component in the exploration task, only the p-value of the mental demand scores of the two modes was significant ($p < 0.05$). In the navigation task, the mental demand ($p < 0.05$) and effort ($p < 0.05$) differences between the two mode maps were statistically significant. We think this is because the self-location and wayfinding in both tasks require higher mental workloads for thinking, deciding, remembering, looking, and searching. The navigation task might require more effort than the free walking in the exploration task. This point was also verified in the interview session.

We also considered the reason that the score differences were non-significant between the two modes for other independent components. We suppose that our task in the experiment was not too difficult in the virtual reality environment compared to the real-world experiment. Therefore, the independent components of physical, temporal demand, performance, and frustration made no significant difference in the two modes. Consequently, we plan to optimize our method and experiment in a more immersive way to simulate a mixed reality environment and will conduct the outdoor field experiment to explore every independent component of the NASA-TLX workload.

Based on the above discussion, we can answer Research Question 2-2 and conclude that the simplified 3D minimap mode decreases the overall workload and the mental demand during exploratory navigation.

5.4.3.3 User experience

Overall, the participants gave higher scores in the positive items for simplified mode, but not all the user experience scores in GUEQ and UEQ were statistically significantly different.

From the interview results, we found that the better user experience also benefited from better performance in navigation. The simplified minimap could help many pedestrians complete the task efficiently. However, for question two (Q2) in GUEQ, for the exploration task, the participants gave a higher score to normal map mode. In other words, most participants considered they could explore things more with normal map mode. Some participants mentioned that the task with the simplified map mode clearly showed the target distribution and route information, so sometimes they only followed the route to arrive at the target. On the contrary, in the task with normal map mode, they needed to recognize the more complicated spatial information, so they paid more attention to every POI surrounding them. Another possible reason we found in the interview was that one participant mentioned that he preferred the complete information for exploration and the simplified mode for precise navigation. The simplified map looks like a tool; in contrast, the mirrored normal mode looks like a map in a treasure-hunting game.

Therefore, we cannot answer Research Question 2-3 by concluding that the simplified 3D minimap mode can result in a better user experience in exploratory navigation. The better user experience during exploratory navigation is also affected by the dynamic pedestrian needs and motivation. Thus, the suitable map interface should be decided on based on the navigation needs during urban exploration.

5.4.3.5 Other findings

We also obtained other findings from the experiment. For instance, we found it interesting that all the participants did not refer to the minimap all the time during navigation tasks in both modes. During the interview process, we asked them about this, and they explained that the minimap looks like a sandbox from a bird's-eye view, which could give them a brief perspective of the surrounding environment. They could establish spatial cognition relatively comprehensively in a short time. In addition, the landmarks with obvious appearance attract participants a lot. Some participants mentioned that they consider the location of the landmarks as a rough direction to navigate and orientate. There exists a lot of studies on exploring the role of landmarks in turn-by-turn navigation [89-92]. Therefore, we believe the landmarks marked in map interface also play an important way in exploratory navigation. Also, we plan to modify our minimap interface to be opened and hidden according to participants' preferences. Another interesting finding is that when asking about the possible use of this concept in the future, more than one pedestrian mentioned in the interview that the simplified minimap could also be used during running, jogging, bicycling, and other outdoor sports in a specific area of the urban environment. This also inspires us to discuss more specific uses for navigation with this system.

We also noticed that some participants mentioned that the minimap could be followed by the motion of the head and eyesight, which inspired us to consider multimodel interaction in the future. In addition, the participants also mentioned that the normal 3D map interface also works in some cases of navigation. For example, the participants said that if the minimap could offer a detailed image of a building from a 3D aerial view, it could help them recognize and identify certain destinations in more complicated environments, for example, an area that has many buildings that have similar appearances and complicated architecture structure. Moreover, one participant suggested that the normal 3D minimap with detailed environmental information could also add the indoor structural information of landmarks and buildings, inspiring us to explore more specific applications of mirrored maps and aerial map modes. Additionally, some participants mentioned that a 3D virtual minimap could also be applied in underground environments where the GPS function might not perform well.

5.5 Limitations and future work

Our method and experiments had limitations, which encourages us to modify our design and conduct more user studies in the future. Firstly, we utilized the virtual reality method to perform the outdoor mixed reality experiment. However, the virtual reality scene we implemented for the experiments was not mirrored and realistic enough to fully simulate the physical environment, which affected our results. Thus, we will implement a more realistic set for outdoor mixed reality experiments and eventually conduct field experiments in the actual outdoor environment to improve the reliability of the results. Secondly, we did not consider classifying different features in the experiments, such as age, gender, and profession. Moreover, some participants also suggested that they expected to interact with the minimap during navigation more diversely, which inspired us to consider navigation interactions in mixed reality devices to provide more interaction with digital information during navigation.

5.6 Answer to research question 2 and conclusion

This work aimed to explore the roles and suitable design of a mixed reality 3D map interface to enhance pedestrians' mental satisfaction in urban exploration.

We designed two experiments to measure the performance of exploratory navigation, perceived workload, and user experience with different modes of the minimap. According to the experiment results, overall, participants had a positive attitude toward the mixed reality 3D minimap concept. We found that the simplified minimap mode can result in lower workload and mental demand, and better performance in specific navigation tasks. However, we could not fully conclude which map mode is suitable for enhancing satisfaction directly because the users' preferences in minimap mode were dynamic.

In the future, we will continue to optimize our methods and experiments to investigate more design insights for map interfaces in mixed reality navigation. We hope this study inspires other researchers in this area to contribute to designing map interfaces for pedestrian navigation and enriching future navigation design.

Chapter 6 Case study: POI visualization methods for promoting urban exploration

6.1 Introduction

Point-of-interest (POI) plays an important role in various geographic information services, helping people quickly locate relevant locations. With the popularization and development of Internet technology, users can conveniently use mobile devices to mark geographical changes that occur around them on the map.

Location-based services and applications have extended the possibility of finding relative information according to the position of the mobile user.

Some of the location-based and context-aware mobile applications focus on providing with POIs to support tourist in learning their surrounding POIs [93, 94]. Some studies make use of the advantages of augmented reality and mixed reality to display the surrounding POIs via virtual mark through the mobile screen interface, but there exist some challenges in this kind of application. Most of these POIs visualization technologies are based on the calculation of the distance between the user and the POI. As a result, sometimes, overwhelmed and overlayed virtual marks of POIs might lead to confusion for the pedestrian. As shown in Figure 45, there exist challenges to POI visualization in navigation interface. In addition, because the needs and motivation in exploratory activities are dynamic, how to push the valuable POIs to the pedestrian in a proper method during urban exploration also needs to be further investigated. For instance, different POI visualization methods may lead to a different performance in different conditions. Thus, in this chapter, we aim to explore the interface design of POI visualization methods to assist pedestrian to discover their surroundings better.

To better answer RQ3: How can we design the POI visualization method for promoting urban exploration? We divided the research questions as follows:

RQ3-1: What are pedestrians' preferences for POI visualization methods in different conditions during exploration?

RQ3-2: Which map modes with virtual information could promote POI awareness of pedestrians in urban exploration?

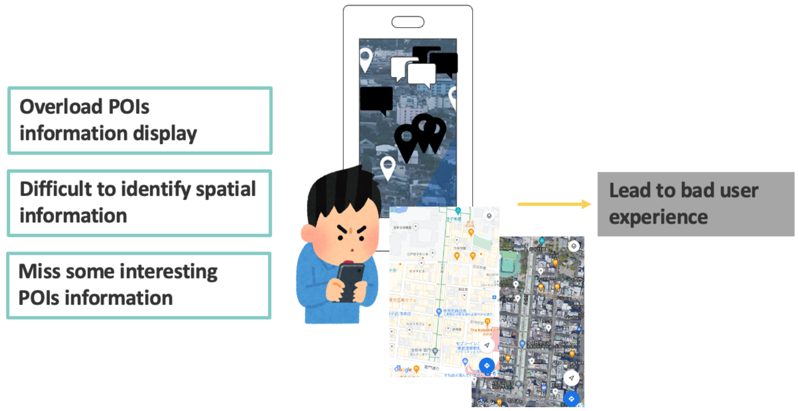


Figure 45 Challenges of POI visualization in navigation interface.

6.2 Study1 Workshop for POI visualization methods

We first conducted a workshop to answer RQ3-1 and specify the requirements and preferences of pedestrians regarding the methods of POI visualization in the navigation interface during specific exploratory activities, we first conducted a workshop to collect the user attitudes and investigate their preference for different POI visualization methods. We implemented six POI visualization methods during exploration in the city environment. We make demonstration for each method in different levels of conditions to explore the user preference for different methods.

We recruited paid 26 participants with age from 22 to 27 years old (10 females, average age = 25 years, SD = 1.97 years). Firstly, we introduce our study and explain the different POI information visualization methods in different scenarios.

To investigate the attitude to interaction with different interface modes and perspectives of view for POI visualization, we used six different POI visualization methods. There exist various studies on how to visualize the POI information through immersive technologies for supporting location-based services, while in this work, we chose 6 common POI visualization methods and discussed the user preference under these six methods. Figure 46 illustrates the six methods' showcase and a detailed description of each method is summarized below.

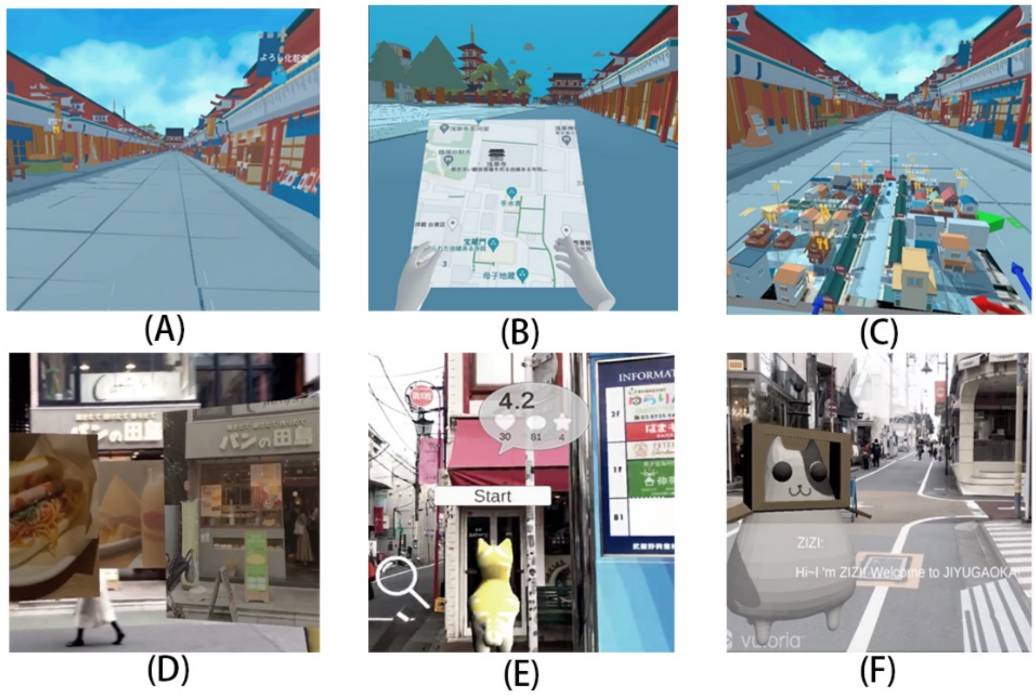


Figure 46 Six POI visualization methods.

6.2.1 POI visualization method description

Mixed reality virtual label:

This method is shown in Figure 46-(A). The method is to overlay location-based POI tags in the real world via a head-mounted display device, with the virtual tags displayed as category labels (e.g., representative tags for restaurants, shopping stores, and attractions) and the name of that POI. An array of virtual marked with different categories of POI on display.

Mixed reality virtual label with 2D map:

This method is shown in Figure 46-(B). The method is based on A with a virtual 2D map. This flat map is like the default 2D mode of Google Maps that we usually use. This map mode has a simplified and clear display of 2D geospatial relationships (e.g., clear routes and distribution of surrounding POIs). Users can browse through the virtual map and interact with it to get more detailed information about POI.

Mixed reality virtual label with hybrid 3D POI map:

This method is shown in Figure 46-(C). The method is based on A with the addition of a virtual 3D map. This 3D map shows almost identical 3D spatial distribution to the real world, and a detailed spatial distribution and appearance composition of surrounding POI can be grasped with a bird's-eye view. Users can browse the virtual map and interact with it to get more detailed information about the POI. The figure shows a 3D model with a really complicated base map interface marked with various POIs. Information displays consisting of directions and distances to intermediate goals.

Virtual images:

This method is shown in Figure 46-(D). This method is designed to provide users with detailed information about a POI to assist in the decision-making process of exploring it. When a user is located at a POI, he or she can view images with detailed information about the POI, which is uploaded and shared by officials and other users from online social media, map navigation services, etc.

Review score:

This method is shown in Figure 46-(E). This method is designed to provide users with rating information on surrounding POI to assist in making decisions about visits during exploration. The ratings are overlaid in the real world in the form of virtual markers based on location, with ratings coming from various review service websites.

Virtual avatar:

This method is shown in Figure 46-(F). The method simulates a virtual assistant guide whose image can be changed according to the user's needs and can be a virtual character, an animal, a robot, and other different types of presence. This virtual assistant aims to provide the user with information about POI and to make recommendations for the user in interactive communication.

Then, we designed factors as three levels during exploration: (1) Wandering without a specific target and with a specific target, (2) Time-limited exploration and exploration, not in a hurry, (3) Pull information from the interface and being pushed by the interface. These three levels can be described in six conditions. The first level was designed to simulate the different walking scenarios, free walking, and specific navigation with the target destination during exploratory activities. The time-limited refers to if the users are in a hurry or not. For example, a user who is in a hurry may prefer efficient methods to acquire more information. The third one was defined as two information conditions the user wants to acquire. For instance, the user wants to browse the POI information from the interface or receive the POIs notification from the interface. After presenting the different POIs visualization methods, we asked them to evaluate each method under six conditions.

6.2.2 Scenario description

"Ming is 23 years old. He is a foreign student at a University in Tokyo. He moved to Japan to pursue his master's degree one year ago, and now he lives by himself. Although he has lived in Japan for one year, sometimes he usually feels that he is not familiar with the neighborhood community and city he lived in. Tokyo is an international city with a lot of city landscapes in diverse characteristic styles. Especially in some city areas, there exists a mixed style of a lot of sightseeing and modern business streets for exploration. Therefore, for the tourist, new residents, and local people, wandering in a city streets block is a good way to explore the city and establish a relationship with the city community.

One weekend day. Ming decided to have a walking in a city street block named Senso-Ji near his residential area, which is a famous tourist street block in Tokyo city. Since he had no time to make a tourism investigation about this street block, he wore his personal mixed reality HMD. This HMD looks like a pair of delicate glasses which can be used as a tool that could display virtual content according to the real-time location during exploration in city streets.

When he arrived at the destination area, he shook his hand, and a virtual map was appearing in his hand. He manipulated the virtual map by transforming, zooming, and rotating with two hands. Through the virtual map, he could have a holistic view of the Senso-Ji and find various POIs marked on the map interface. Once he specifies a POI, he would wander in a rough direction, refer to the virtual map and eventually arrive at the destination POI he wants to explore. If he wants to learn more about the target POI, he can browse the virtual content from the interface. During wandering, he did not open the mixed reality virtual map all the time. Sometimes, the virtual map will also push the POI information during free wandering. In brief, he could pull the virtual map as his preference and need, while he would be notified by the map. In this way, Ming explored the whole Senso-Ji."

6.2.3 Workshop process

We conduct the workshop through online meetings and interviews. The detailed processes of the workshop are described in Table 5. We first asked each participant for approval of the informed consent form.

Table 5 Workshop process description

PROCESS	METHOD	DETAIL
INTRODUCTION	Background Introduction.	
DEMONSTRATION	• Showcase and introduction for each method. • Description of three factors with six conditions.	
USE CASE PROPOSAL	• Semi-structured Interview. • 7 Likert scale Questionnaires.	• Use Case Scenario description. Requirements and Needs. • Preference Grading for Different Methods.
INTERACTION PROPOSAL	Picture Drawing	• Interaction Method with the Different POIs information. • Relationship between the users and the POI.

We showed six POI visualization methods to them and gave a detailed description of each method. Then we explained our three factors with six conditions and were asked to evaluate their preference respectively according to their preference.

6.2.4 Results and discussion

The workshop questionnaire results, and all interview results are summarized. Figures 47-49 show the average value for every method in three levels.

- *Quantitative results*

The data of preference evaluation was analyzed by two-way ANOVA ($\alpha = 0.05$) with replication and Bonferroni-adjusted post hoc tests when the results indicated a main effect. The results are shown in Tables 6-8.

As shown in Table 3, we asked each participant to grade the preference for the different POI visualization methods in level: with a target and without a target. Results indicated a main effect in the "Target" level ($p<0.01$). Also, an interaction effect between "Target" and methods ($p<0.05$). The post hoc tests indicate that method A, mixed reality virtual label, performed better in "without target" than in "with target" ($p=0.001$). We suppose that without the specific target, the participants prefer the natural, seamless notification of POI in exploration. On the other hand, method B, mixed reality virtual label with 2D map, performed better in "with target" ($p=0.03$) compared to "without target". We consider this because a 2D map is efficient for the distribution of POIs and route information.

Table 6 Two-way ANOVA with replication for whether users walking with a target or not.

ANOVA			Target			
Source of Variation	SS	df	MS	F	P-value	F crit
Level	17.333	1.000	17.333	7.395	0.007**	3.907
Method	32.205	5.000	6.441	2.748	0.021*	2.277
Interaction	32.513	5.000	6.503	2.774	0.020*	2.277
Within	337.538	144.000	2.344			
Total	419.590	155.000				

* p<0.05 ** p<0.01

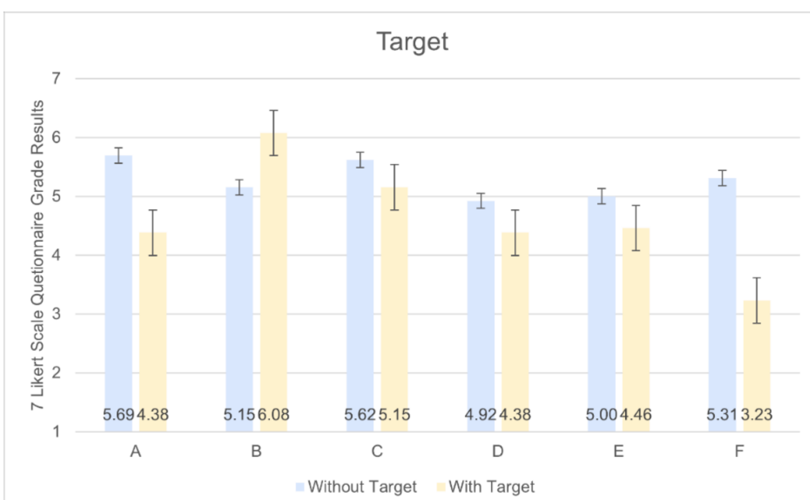


Figure 47 Mean preference values for POI visualization methods with or without the target. Error bars indicate standard error.

As shown in Table 4, participants evaluate the preference for each method in level: in a hurry and not in a hurry. No main effect in the "Time" level (p>0.05).

But results show an interaction effect between "Time" and methods (p<0.01).

The post hoc tests show that method B, mixed reality virtual label with 2D map, performed better in "in a hurry" compared to "not in a hurry" (p=0.03).

Like the results in level "Target", we think it is because of the advantage of the 2D map in a limited time, which could make participants acquire the distribution of POIs and routes information efficiently.

Table 7 Two-way ANOVA with replication for whether users are in a hurry or not

ANOVA			Time			
Source of Variation	SS	df	MS	F	P-value	F crit
Level	6.160	1	6.160	3.258	0.073	3.907
Method	26.494	5	5.299	2.802	0.019*	2.277
Interaction	36.186	5	7.237	3.827	0.003**	2.277
Within	272.308	144	1.891			
Total	341.147	155				

* p<0.05 ** p<0.01

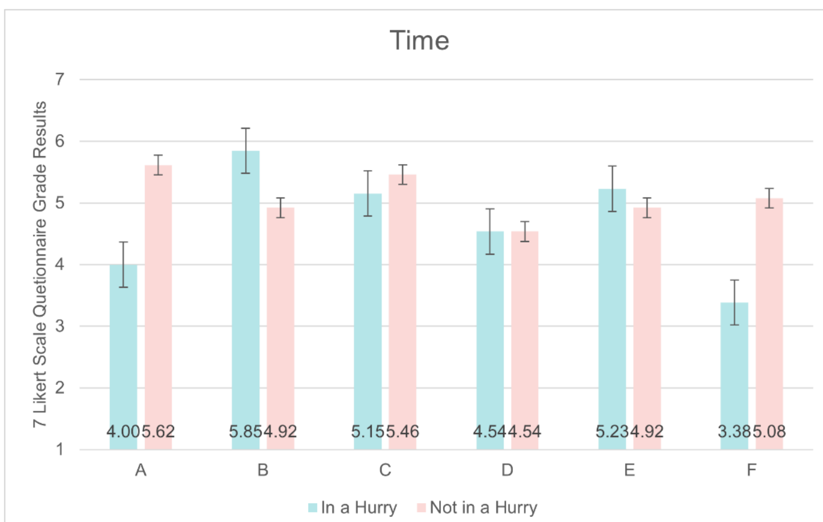


Figure 48 Mean preference values for POI visualization methods in or not in a hurry. Error bars indicate standard error.

As shown in Table 5, there is no main effect in level "Pull and Push" (p>0.05). And results indicate an interaction effect between "Pull and Push" and methods(p<0.05). For post hoc tests, the results show that only method B, mixed reality virtual label with 2D map, performed better in "Pull" than in "Push" (p=0.01). This means that the 2D map has relatively much more functional and clear information for "Pull", and other POI visualization methods have no significant differences in this level.

Table 8 Two-way ANOVA with replication for whether users want "Pull" or "Push" information.

ANOVA			Pull and Push			
Source of Variation	SS	df	MS	F	P-value	F crit
Level	1.853	1	1.853	1.074	0.302	3.907
Method	3.109	5	0.622	0.361	0.875	2.277
Interaction	23.417	5	4.683	2.716	0.022*	2.277
Within	248.308	144	1.724			
Total	276.686	155				

* p<0.05 ** p<0.01

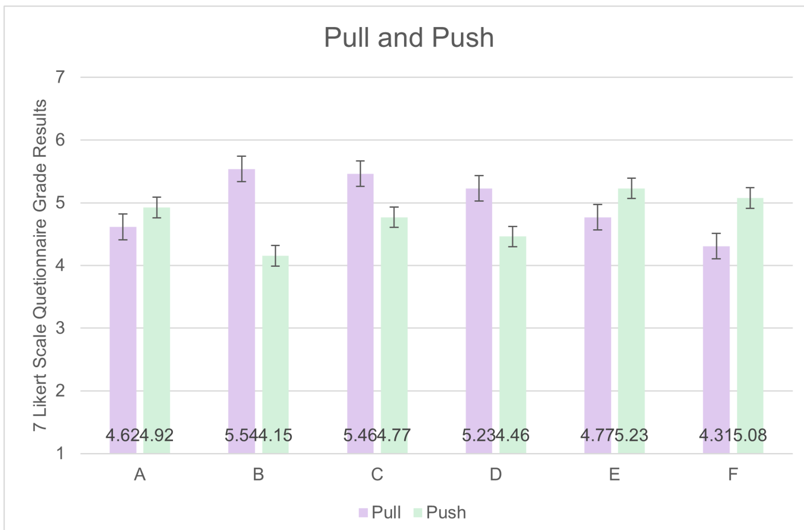


Figure 49 Mean preference values for POI visualization methods for "Pull" or "Push" information. Error bars indicate standard error.

- Qualitative results

After evaluating the preference grade for each method in three different levels, we also conducted a semi-structured interview. To investigate the specific method used in different scenarios and the interaction with the interface, we asked participants to give a description for three interface modes: 2D map; 3D hybrid map; location-based virtual content to augment the real world; virtual avatar as an assistant for recommendation and guidance.

The questions and the interview answer are summarized in Table 9.

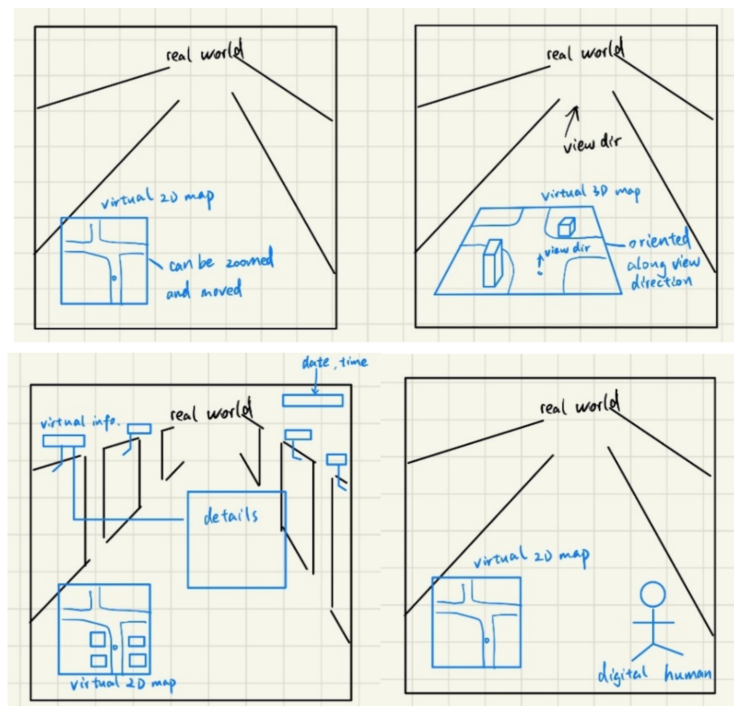
We also asked each participant to draw the relationship between themselves and the interface modes (2D map, 3D map, virtual contents, and virtual avatar).

From the submitted illustration, we select several ones to represent the majority proposal in Figure 50.

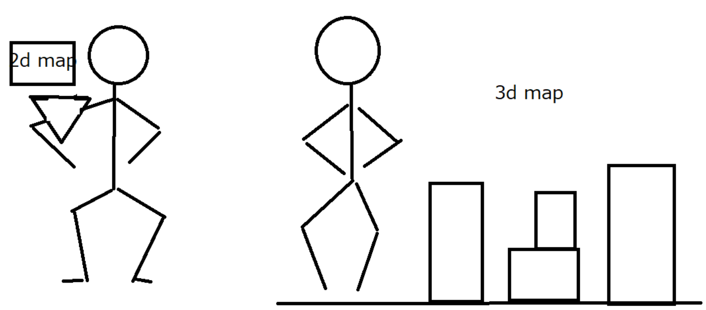
Table 9 Interview Results of Workshop

	2D virtual map	3D hybrid virtual map	Virtual contents related to the POIs	Virtual character avatar
Where do you like to user this interface to acquire the POIs information?	In a busy city streets block with complicated spatial distribution. In a destination that surrounded a lot of POIs. In a destination with a relatively clear POIs distribution.	In a destination area with an attractive and unique style. In a building group with attractive architectural aesthetics. In a city tourism area with sightseeings and business street. In a complicated indoor environment.	In a city streets block with an attractive and unique style. In a destination with numerous and diversied POIs. Anywhere(not just for tourism and exploration, also for learn about the information for stores and facilities in city)	In a destination with numerous and diversied POIs. In a destination with an intensive POIs distribution.
When do you like to use this interface to acquire the POIs information?	When users want to grasb the overall POIs distribution at the begining. When users want to know the route informtion to arrive at a target POI. When users want to acquire much more POIs distribution efficiently in a limited time.	When users want to explore the famous landmarks and sight seeings in city. When users want to decide whether he or she will explore according to the appearance of POIs. When users want to know the exact entrance and spatial scale of POIs. When users cannot recognize the spatial information clearly from the 2D map.	When users just want to enjoy the street view without the map and navigation. When users in free walking aimlessly. When users want to learn about the information(images, review scores) of the restaurants, cafe and stores. When users want to learn more detail information about a target POIs.	When users want to acquire some recommendations. When users have a direction of category but without a specific target. When users have free walking aimlessly. When users want to acquire the navigation instruction. When users want to learn information off-screen the map interface. When users want to free their hands and just focus on observing the surrounding.
What kind of information about POIs do you prefer from this interface?	Self location Name of POIs Category of POIs Review score of POIs Landmarks, popular POIs Business information Distance from the POIs Arriving time Destination area range Clear route distribution	Self location Name of POIs Category of POIs Review score of POIs Landmarks, popular POIs Architecture appeareance Charateristic style Entrance location Indoor information Terrian	Name of POIs Category of POIs Review score of POIs Images of POIs Popular contents from SNS	Name of POIs Category of POIs Review score of POIs Personal recommendation Recommendation reasons Story and cultural background Navigation instruction A series of POIs with the same category. Popular POIs
How do you like to interact with this interface?	Hand gesture Speech Eye-tracking Wearable device Controller	Hand gesture Speech Eye-tracking Wearable device Controller	Hand gesture Speech Eye-tracking Wearable device Controller	Hand gesture Speech Eye-tracking Wearable device Controller

(A) Participants 6



(B) Participants 26



(C) Participants 12

Figure 50 Proposal drawing from participants 6(A), 26(B) and 12(C).

- *Discussion*

According to our workshop results, we found that the preferences for using different types of modes and different kinds of POI information are dynamic according to users' current needs and situations. We also found that different types of POI are also required in different contexts. For instance, users prefer browsing the POIs and POI distribution at the beginning of exploration. Except in a hurry time and with a specific target destination, users prefer an interface that could inspire them to decide which POI to explore.

- *2D virtual map*

According to the results, we could find that because of the clear information on the 2D map, participants prefer to acquire more basic information about POIs. For instance, in busy city street blocks with complicated spatial distribution, participants like to utilize the 2D map to acquire much more information, like the distribution of POIs efficiently in a limited time and route information if they need to arrive at a target POI.

For information types, location information, basic information related to POI, transportation information, navigation information is required in specific condition. The interaction methods are mostly preferred as a small-scale hand gesture. From the submission of the relationship between users and the 2D map, all the participants (26) drew a 2D map in front of the user and from a vertical perspective. And the scale of the 2D map is relatively small, like a minimap.

- *3D hybrid virtual map*

The results indicate that participants preferred to acquire the architectural appearance from the 3D map interface. For example, P5 mentioned that he would like to make an exploration decision according to the unique style of some building groups and city landscape. However, not all the participants utilized the 3D map for POI exploration decisions. P7 said that she might use the 3D map to recognize the entrance to support her arriving at the right destination sometimes.

The preferred information in the 3D map is similar to the 2D map, while some participants mentioned that they also prefer to acquire the indoor information in a 3D model on the map, that it can help them to decide whether they will enter or not. The most answer for the interaction method is hand gestures. From the submission of the drawing, all the participants drew the 3D map interface in bird's-eye view, but the scale of the 3D map had different answers. P16 suggested that he would like to zoom in and out the 3D map as she wants.

- *Virtual content related to the POI*

The attitudes towards virtual content related to POI mainly focus on if it can assist them in deciding whether they will explore the POI. For example, in the interview, we know that images are preferred when the user wants to know detailed information on a POI, such as the menu of a restaurant, facilities, atmosphere, and so on. On the other hand, the review score is more popular for users who have a decided category. For instance, P10 explained that when he decides to go to a restaurant, he would like to use the review score for all restaurants, so he can decide efficiently when in a hurry.

Some participants prefer eye-tracking and speech methods for the interaction method with the virtual content, which differs from the most answer in the 2D and 3D maps. However, it is interesting that P8 mentioned she could save the virtual contents she is interested in and visit this POI the next time. In addition, some participants said that the virtual information could be active when he arrives at a POI or enter a POI.

- *Virtual avatar*

The attitude towards the virtual avatar is dependent on various factors. Most of the answer for when they would like to use a virtual avatar is traveling alone. The avatar category is also a crucial factor for using this kind of navigation to explore. For the information types of POI, most participants said they wanted personal recommendation and cultural backgrounds and stories in some famous streets and sightseeing. The preference for interaction method mainly focused on speech interaction. However, many participants mentioned that the speech interaction in public might lead to a bad experience, so they also prefer to utilize the mixed interaction methods according to the real-time condition.

6.3 Study 2 Different map modes with virtual information to promote POI awareness

Based on study 1, we designed study 2 to answer RQ3-2 and investigate the different map modes with virtual information to promote POI awareness of pedestrians in urban exploration.

6.3.1 Research approach

Arriving in a new urban thematic tourism and walking area may be exciting. However, it usually causes anxiety and confusion about exploring a complicated street area. Navigation assistance, from paper maps to digital applications, are designed to support urban exploration. However, many of them need to be better suited for pedestrians, especially in unfamiliar urban areas, where contexts depend on the situation and preferences of users vary from person to person.

Therefore, in this study, we propose different map interfaces with different visualization of POI methods, allowing pedestrians to identify various POI information and engage experience in exploration.

To investigate what kind of information could promote pedestrian POI awareness and engage the pedestrian to explore much more POIs during exploration, we designed an experiment with four map interfaces that were augmented with different kinds of POI information. We will introduce each interface mode below.

- *2D map with POI category label*

2D maps provide survey knowledge to help people build an accurate mental model or a cognitive map of the environment. Based on the previous work, we found that users like to use 2D maps to grab the overall distribution of POIs and consider the 2D map as a minimap to learn clear information briefly.

Thus, in the interface mode, we designed a 2D minimap in front of the head and marked the POI category label on the map, shown in Figure 51.

Figure 51 2D Map with POI Category Label.

- *2D map with POI category label and images*

Images can provide pedestrians with visual stimulation, which might attract them to explore the POI. The results of study 1 indicate that the majority of the participants would like to refer to the images related to POI can help users learn the POI efficiently. Thus, in this experiment, we make use of the vertical space of a bird's-eye view virtual map to display the images of POI, which is shown in Figure 52. The map interface is designed as a paper map in hands in a bird's-eye view. The virtual pictures of POIs are displayed. In addition, users can browse the Category label of all the distribution of POIs.

Figure 52 2D Map with POI Category Label and Images.

- *2D map with POI category label and virtual avatar*

Virtual character avatars could provide pedestrians with detailed location-based POI information in an interesting way, such as gamification and storytelling. Thus, the pedestrian could learn the POI information via communication with the virtual assistant. As shown in Figure 53, in this study, we designed a virtual character to simulate the virtual assistant and provide pedestrians with highlighted POIs as a recommendation.

Figure 53 2D Map with POI Category Label and Virtual Avatar.

- *2D map with POI category label and hybrid 3D POIs*

3D hybrid POIs are virtual models that replicate the visual characteristics of their physical POIs. In contrast to the 2D map, the 3D map may allow any vantage point. It may be tied to the viewer's location and orientation, or the viewer may choose to roam freely.

In this study, we select POIs whose appearance is unique and have characteristic styles. We want to investigate whether the 3D POI appearance is attractive enough for exploration decision-making during exploration, as shown in Figure 54.

Figure 54 2D Map with POI Category Label and Hybrid 3D POIs.

6.3.2 Implementation and experiment design

We built a virtual reality experiment to simulate mixed reality exploratory navigation via HMDs in urban streets area outdoors. In this study, we use Oculus quest 2 as a virtual reality headset connected to a personal computer.

The virtual city scene is implemented by 3D city models downloaded from the unity asset store. We implemented a business city street block with a unique style and set a series of POIs both in the virtual map and the city scene. Figure 55 shows a view of a virtual scene in our experiment.

We design two tasks for POI awareness and engagement of exploration with different map modes, comparing the proposed four interface modes.

Our goal was to collect data for analysis of the behavior and preference of users. Each task required subjects to identify several labeled targets (POIs). In addition, we record the time-to-insight and visited POIs numbers. The experiment tasks are described as shown in Table 10 below.

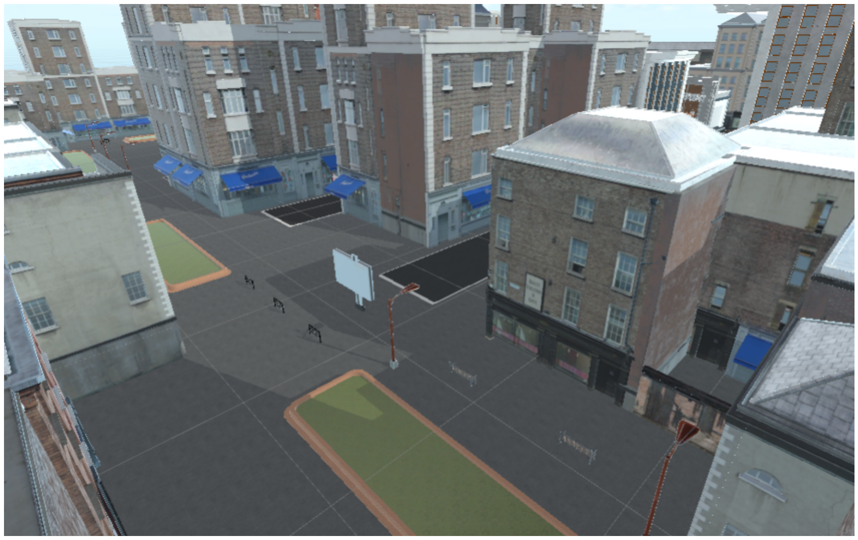


Figure 55 Virtual city scene used in the experiment.

6.3.3 Participants

We recruited 10 participants (4 females) with an average age=26 years, SD=2.42 years to participate in the experiment.

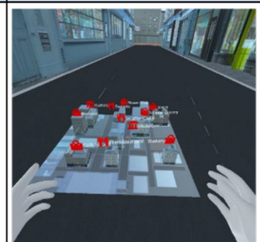
As shown in Table 10, each participant was introduced to the background of this study. Then they were asked to wear the Oculus quest 2 to practice the operation in a practice scene to complete a simple wayfinding task referring to our different map interfaces. After being familiar with the controller and operation in the virtual scene, each participant was asked to enter one interface mode randomly and start from a random location in the virtual scene.

In task 1, participants are asked to use different map modes to decide which POI they would like to explore at the beginning of the exploration. The time from the beginning signal to completing the decision response was recorded at every turn of task 1.

In task 2, participants are asked to use different map modes to explore the POIs marked in the interface as their preference in an assigned session. In addition, POIs visiting rate will be recorded (the number of visited POIs).

After every task session, we asked each participant to evaluate the experience of "helpful," "engagement," and "attractive."

Table 10 Experiment design

Map Mode	Category Label	Images	Avatar	Hybrid 3D POIs
Illustration				
Implementation	2D virtual map base Category Label	2D virtual map base Category Label Images of POIs	2D virtual map base Category Label Highlight POIs	2D virtual map base Category Label
Description	The map interface is designed as a minimap in orthographic view on the front-upward of the users. Users can browse the Category label of all of the POIs distribution.	The map interface is designed as a paper map in hands in bird's-eye view. Virtual pictures of POIs are displayed. Users can browse the Category label of all of the POIs distribution.	Based on the first map mode, this mode add a virtual avatar to make a dialogue with users to recommend a series of POIs. The recommended POIs are highlighted by star.	The map interface is designed as a paper map in hands in bird's-eye view. Realistic Virtual 3D model of POIs are displayed. Users can browse the Category label of all of the POIs distribution.
Practice Mode	Each participant is asked to get familiar with the operation in the virtual scene via VR headset and controllers			
Task1	POI Decision-making			
Task Description	In this task, participants are asked to use different map modes to decide which POI they would like to explore at the beganing of exploration.			
Measurement	POI decision time will be recorded (the time from beganing signal to completing the decision respond)			
Task2	POI Exploration			
Task Description	In this task, participants are asked to use different map modes to explore the POIs marked in the interface as their preference in an assigned session.			
Measurement	POIs visiting rate will be recorded(the number of visited POIs)			
User Preference	Interview and preference evaluation of helpful, engagement and attractive			

6.3.4 Results and discussion

The results of study 2 are summarized in Figure 56-58 and Table 11.

The data was analyzed by single-factor ANOVA ($\alpha = 0.05$). Results indicate that though the average value of a 2D virtual map base with category labels and images varies, POIs Decision Time among each interface mode has no significant difference ($p>0.05$).

On the other hand, the results show that the POIs visiting Rate has the main effect among different interface modes ($p=0.0058$). The results show that the virtual avatar interface mode makes participants visit many more POIs.

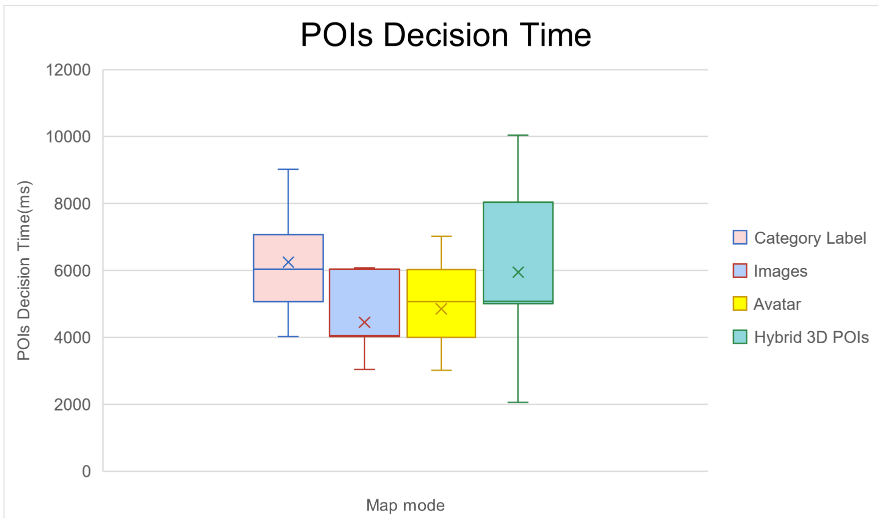


Figure 56 Box plot for POIs Decision Time.

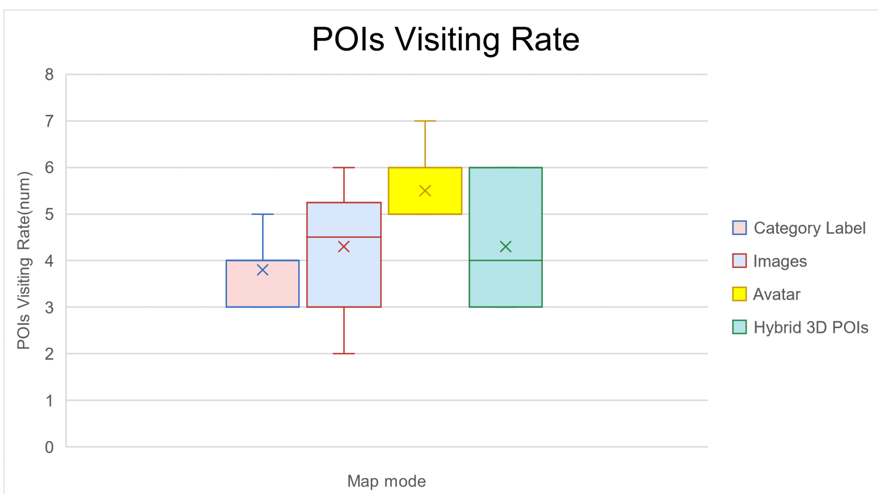


Figure 57 Box plot for POIs Visiting Rate.

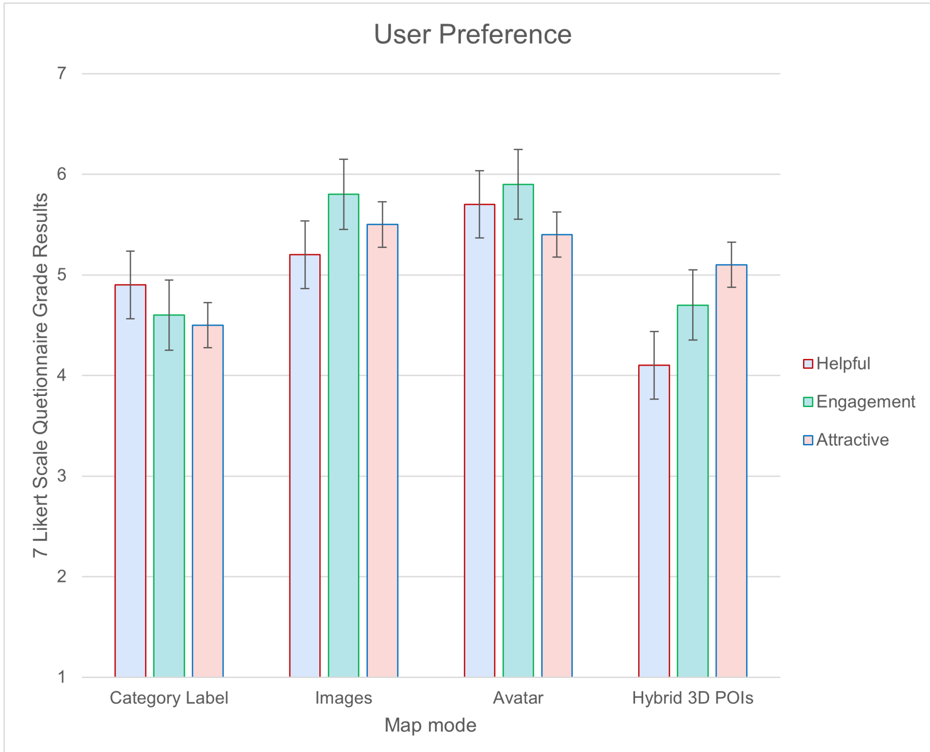


Figure 58 Preference evaluation for three questions on "Helpful", "Engagement", and "Attractive" based on user experience.

Table 11 Answers of impactful kinds of information and their rank.

	Category Label Task	Images Task	Avatar Task	Hybrid 3D POIs Task
What are the impactful information for you to decide to visit a POI? And please give a rank for them.	**1. Category Label** 2. Distance 3. Name	**1. Images** 2. Distance 3. Category Label 4. Name	**1. Recommendation Highlight** 2. Distance 3. Introduction and Guidance 4. Category Label	**1. POI 3D Appearance** 2. Category Label 3.Distance

The results indicate that the user preference of experience for "helpful" and "engagement" have a main effect for different interface modes ($p<0.05$), but there is no main effect for "attractive" ($p>0.05$), the mean values of three questions are shown in Figure 55.

We also asked participants to rank the kinds of POI information. The answers are in Table 8. The results indicate that when information is rich with mixed reality features such as virtual images, virtual avatars, and virtual 3D models, the exploration decision is influenced more by these kinds of information.

6.4 Answer to research question 3 and conclusion

In this chapter, we design two studies to explore the different POI visualization methods in mixed reality features. First, we compare the user preference to different POI visualization methods in different conditions and investigate the interaction effect between the different condition levels and the methods. The results indicate an interaction effect between the three levels (Target, Time, and Pull and Push) and visualization methods.

As for research question 3, we could answer that we should design the POI information methods according to the dynamic conditions, and the visualization method should be designed to be switchable to respond to different conditions. The results also indicate that the recommendation from the virtual avatar and the virtual contents with mixed reality features could help and engage the pedestrian to explore much more POIs, but we cannot conclude that pedestrians are satisfied with all the POIs they decide to explore. Therefore, we should consider POI satisfaction evaluation in design consideration.

Based on the data analysis and interview, we extract the specific scenarios, timing, and POI information kinds for different interface types. We also summarized the design consideration for future mixed reality exploratory navigation to visualize the location-based POIs. According to our results, the switchable visualization method according to dynamic conditions in real-time is valuable to discuss further.

Moreover, diverse conditions need to be explored in the future. In our work, we focus on walking without a target and with a target, time in a hurry or not in a hurry, and pull or push information. However, the context during exploratory navigation is more complicated than these conditions, therefore we advocate researchers conduct further research. Finally, this research was conducted via the virtual reality headset to simulate mixed reality in city streets outdoors. In the future, we still need more field experiments to conclude a more concrete conclusion.

Chapter 7 Design insight for future mixed reality exploratory navigation interface

In this chapter, we make a general discussion and discussion of each research question for this work and summarize the design insight for future direction.

7.1 General discussion

From the results, we were able to summarize more comprehensive user requirements for pedestrian exploratory navigation in the urban context. Based on our case study results, we can identify the design insight of new possibilities via mobile mixed reality exploratory navigation in the future. This work suggests and advocates other researchers in HCI to pay attention to interactive mixed reality navigation interface design for urban exploration. We hope this work will inspire deep HCI research and provide a new value for future mixed reality application design in a smart environment.

Future work will expand diverse and comprehensive evaluation methods for pedestrian satisfaction and user experience in this kind of application. For instance, we need to consider how to collect both intrinsic and extrinsic needs of the pedestrian during exploration in an urban scenario to design and implement the adaptive interface of mixed reality navigation. Furthermore, we need to specify pedestrians' real-time context as input for more adaptive mixed reality applications and then adapt various interface factors such as the placement, appearance, and level of detail of the virtual interface elements as the output of the system. Moreover, how to integrate this kind of navigation into daily life and design more mindfulness and seamless interaction for context switching is also an essential research consideration in the future.

7.2 Discussion for each research question

- RQ1: What are the pedestrians' needs and preferences for virtual interfaces in urban exploration?

In Chapter 4, we added two interactive interest-based features to the normal navigation system and designed case study to investigate the interaction expectation of pedestrians in urban contexts. We found that the user requirements and interaction expectations with the real world and virtual content in exploration are different and dynamic. The different interface components in exploratory navigation could engage the participants in urban exploration, while the interaction between the pedestrian and virtual content should not be isolated, to the opposite, it should relate to the physical world. In addition, the interaction between the pedestrian and the virtual interface components should also be designed according to different scenarios.

- RQ2: How can we design the virtual map for promoting urban exploration?

In Chapter 5, we proposed a novel map interface as a part of mixed reality navigation for urban exploration. As the outdoor mobile mixed reality via HMD technologies are not yet widely adopted and developed, the prototype we implemented in a virtual city scene could provide users with a fresh experience and inspire other researchers for future possibilities.

- RQ3: How can we design the POI visualization method for promoting urban exploration?

In Chapter 6, we first conducted a workshop as study 1 to discuss different POI visualization methods in different conditions. Based on our study, we summarized the specific scenarios and timing for different types of methods and investigated the practical use proposal for them. Then, to furthermore investigate the effect of different kinds of POI information, we design four interface modes to measure the awareness of the decision to explore a POI and which kinds of POI information perform well in promoting pedestrians to visit much more POIs during exploration. Our results indicate that the rank of the POI information types which could help and engage pedestrians to visit much more is the virtual avatar, images and 3D POIs, and category labels. We believe that the "pushed" information from the recommendation and the visual information could engage pedestrians in exploration. However, we also find that the pedestrian needs a mixed method during exploration, and sometimes, they would like to switch the method according to their requirements in real-time.

7.3 Future direction for each research question

In this dissertation, we explore the interface design of mixed reality navigation for engaging urban exploration. We expect the design insights presented here to be used in academic research and practical industrial applications as guidance. Thus, in this section, we detail future challenges and directions for each RQ.

7.3.1 Future direction for research question 1

We explored the user requirements and interaction expectation for virtual interface of pedestrians in city exploration. We developed two systems and designed a case study to evaluate user experiences and observed their interaction behavior during user study. Our system encouraged participants to explore their city and learn more location-based information. Based on the results, we summarized the user interaction expectation to map interface and POI visualization in different scenarios.

Therefore, the map interface and the method for POI visualization in exploratory navigation should be designed adaptive in different contexts depending on different demands and preferences. Furthermore, the interaction between the pedestrian and the virtual content via exploratory navigation needs to be related to the physical environment. In the future, we encourage the researcher in this field further investigate pedestrian motivation and needs in various contexts to enrich the design diagram.

7.3.2 Future direction for research question 2

We designed two experiments to measure the performance of exploratory navigation, perceived workload, and user experience with different modes of the minimap. In addition, we summarized future directions that may inspire further studies in this research area. Firstly, what kinds of spatial information should be simplified still needs more discussion in the future. Additionally, the proposed simplified mode filters irrelevant information and maintains the 2D base map layer. However, some participants mentioned that this would damage the spatial structure and distribution, which also inspires us to weaken the details of some irrelevant POIs and retain the 3D features, such as size and location, instead of filtering them directly into the 2D view. In addition, from the interview, we found that except for walking during exploratory navigation in urban streets, the 3D minimap interface could also be used in theme parks and wild forest parks for exploration. Therefore, we advocate further research to discuss more specific uses of mixed reality maps.

Additionally, researchers could focus on combining this kind of map interface with location-based augmented reality and mixed reality games in the real world to make pedestrians become players in exploring the real world. Therefore, the interaction between the pedestrian and the interfaces should be designed comfortable and seamless. Finally, the experimental design in this work did not involve different groups of participants. Therefore, researchers in this area can discuss these issues further.

7.3.3 Future direction for research question 3

In case study 3, we designed two studies to explore the different POI visualization methods in mixed reality features. First, we compare the user preference to different POI visualization methods in different conditions and investigate the interaction effect between the different condition levels and the methods. The results indicate an interaction effect between the three levels (Target, Time, and Pull and Push) and visualization methods. Based on the data analysis and interview, we extract the specific scenarios, timing, and POI information kinds for different interface types. We also summarized the design consideration for future mixed reality exploratory navigation to visualize the location-based POIs. Firstly, we suggest considering a switchable visualization method according to dynamic conditions in real-time. Then, more conditions need to be explored in the future. In our work, we focus on walking without a target and with a target, time in a hurry or not in a hurry, and pull-push information. However, the context during exploratory navigation is more complicated than these conditions, so we advocate that other researcher conduct further research. Finally, this research was conducted via the virtual reality headset to simulate outdoor mixed reality in city streets. Utilizing virtual reality to simulate mixed reality outdoors could provide free design space for imagination at the beginning. However, we still need more field experiments to conclude a more concrete conclusion.

Chapter 8 Conclusions

In this work, we attempt to focus on the user interface of future novel navigation via a head-mounted display from the perspective of human-computer interaction design to promote the user experience in exploratory navigation, discussing more possibilities of interaction in urban exploration and thus providing more reflection and insights for the design of future mobile mixed reality navigation systems. To better investigate the design framework for future mixed reality exploratory navigation in urban exploration, we aim to explore the effects of the virtual interface of location-based mixed reality navigation on pedestrians' exploration engagement, investigate the role of the virtual map of navigation interface on pedestrian exploration, and design interaction methods for pedestrians to interact with the POIs information visualized on the interface. We designed three case studies and conducted experiments to discuss and summarize the design insights for future mixed reality navigation to support urban exploration.

In the first case study, we designed location-based gamified interactive mobile augmented reality navigation and virtual reality city tour navigation to explore the interaction expectations of pedestrians during urban exploration via such exploratory navigation. Furthermore, we combined gamification with mobile augmented reality navigation to study the effects of the interest-based navigation interface on pedestrians.

Based on our user studies, we summarized the interaction expectations during exploratory navigation and proposed design insights of the gamification mechanism for exploratory navigation to engage pedestrians in exploration.

We also explore the effects of the virtual interface of mixed reality navigation in urban contexts. Based on our results, we found that the gamification mechanism and gamified interaction between pedestrians and the virtual character could help them acquire more exploratory information and engage them in exploration. Moreover, we summarized the interaction preference between the pedestrian and navigation interface.

In the second case study, we designed an interactive virtual map interface through mixed reality HMD. We use the advantage of the interactive mixed reality map to increase the interactivity between pedestrian and virtual content rather than just displaying the virtual marks through hand-held augmented reality navigation. Furthermore, we explored the role of the virtual map interface in mixed reality exploratory navigation and discussed the level of detail of map design to promote pedestrian satisfaction during urban exploration. The experiment results showed participants a positive attitude toward our method. In addition, the different levels of detail of the map interface could result in various performances and experiences in specific navigation tasks.

In the third case study, we designed different visualization methods for POI. We explored the interaction effect with specific scenarios to explore how to design the POI visualization method to respond to dynamic needs and motivation during exploration in complicated contexts. We found that pedestrians prefer to switch different POI visualization methods dynamically during exploration according to their current conditions. The interaction between them and the information method should be more comfortable and context aware.

Based on the above studies' results, we summarized and discussed the design consideration and future direction in Chapter 7 and expected our work to inspire further studies and provide a design consideration for future mixed reality navigation with HMDs applied in urban exploratory navigation.

However, our methods have limitations. Firstly, most experiments are conducted via virtual reality to simulate the outdoor mixed reality features. We hope to use the advantages of virtual reality headsets to expand the design idea at the beginning of the studies, but we still need further field studies to make the results concrete. Secondly, our research scenarios are all in thematic city streets in Tokyo, Japan, which consists of the characteristic style in numerous city landscapes and tourist destinations. Our work utilizes these kinds of city scenarios as case studies. Still, we also need to involve different types of the city with diverse backgrounds and cultures of users worldwide to find more design insights for future mixed reality exploratory navigation. In addition, in our three case studies, the majority of the participants consider the safety problem important for this kind of navigation via HMDs, which we also think it is an essential issue which we should pay attention to in the future. Therefore, we will also add the consideration of safety issue to the interface design to continue enriching the design diagram of future mixed reality navigation via HMDs.

Finally, we also have several visions for future work. Firstly, we hope this work could provide design insight and consideration for interface design of the future mixed reality navigation. The design diagram of mixed reality exploratory navigation should be expanded in the future to satisfy the different layers of pedestrian needs. Then we also expect that the results of this work could also be referred to in virtual environments like virtual city tour and metaverse in the future.

REFERENCES

[1]. Anderson, Z.; Jones, M.D. Mobile computing and well-being in the outdoors. In Proceedings of the Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers, London, UK, 9–13 September 2019; pp. 1154–1157.

[2]. Neal, J.D.; Uysal, M.; Sirgy, J.M. The Effect of Tourism Services on Travelers' Quality of Life. J. Travel Res. 2007, vol. 46, pp. 154–163. DOI: https://doi.org/10.1177/0047287507303977

[3]. Buhalis D, Amaranggana A. Smart Tourism Destinations Enhancing Tourism Experience Through Personalisation of Services. In: Tussyadiah I, Inversini A, editors. Information and Communication Technologies in Tourism 2015. Cham: Springer International Publishing; 2015, pp. 377–89. DOI: https://doi.org/10.1007/978-3-319-14343-9_28.

[4]. Holton, M. Walking with technology: Understanding mobility-technology assemblages. Mobilities 2019, vol. 14, pp. 435–451, DOI:10.1080/17450101.2019.1580866.

[5]. Kim, D.; Kim, S. The Role of Mobile Technology in Tourism: Patents, Articles, News, and Mobile Tour App Reviews. Sustainability 2017, vol. 9, no. 2082. DOI:10.3390/su9112082.

[6]. Richardson, I.; Wilken, R. Haptic vision, footwork, place-making: A peripatetic phenomenology of the mobile phone pedestrian. Second. Nature: Int. J. Creat. Media 2009, vol. 1, pp. 22–41.

[7]. Cartwright, W.; Peterson, M.; Gartner, G.; Reichenbacher, T. Adaptation in mobile and ubiquitous cartography. 2007.

[8]. Nayyar, A.; Mahapatra, B.; Le, D.-N.; G, S. Virtual Reality (VR) & Augmented Reality (Augmented reality) technologies for tourism and hospitality industry. International Journal of Engineering and Technology (UAE) 2018, 7. DOI:10.14419/ijet. v7i2.21.11858.

[9]. Rokhsaritalemi, S.; Sadeghi-Niaraki, A.; Kang, H.-S.; Lee, J.-W.; Choi, S.-M. Ubiquitous Tourist System Based on Multicriteria Decision Making and Augmented Reality. Applied Sciences 2022, 12. DOI:10.3390/app12105241.

[10]. Yung, R.; Khoo-Lattimore, C. New realities: a systematic literature review on virtual reality and augmented reality in tourism research. Current Issues in Tourism 2017, vol. 22, pp. 2056-2081. DOI:10.1080/13683500.2017.1417359.

[11]. Moro, S.; Rita, P.; Ramos, P.; Esmerado, J. Analysing recent augmented and virtual reality developments in tourism. Journal of Hospitality and Tourism Technology 2019, vol. 10. DOI:10.1108/JHTT-07-2018-0059.

[12]. Ahmadpoor, N.; Shahab, S. Spatial Knowledge Acquisition in the Process of Navigation: A Review. Current Urban Studies 2019, vol. 7, pp. 1-19. DOI:10.4236/cus.2019.71001.

[13]. Lee, J.; Jin, F.; Kim, Y.; Lindlbauer, D. User Preference for Navigation Instructions in Mixed Reality. In Proceedings of the 2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 2022, pp. 802-811.

[14]. Thi Minh Tran, T.; Parker, C. Designing Exocentric Pedestrian Navigation for Augmented reality Head Mounted Displays. In Proceedings of the Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, 202, pp. 1-8.

[15]. Bujari, A.; Gaggi, O.; Palazzi, C.E. A mobile sensing and visualization platform for environmental data. Pervasive and Mobile Computing 2020, vol. 66. DOI: 10.1016/j.pmcj.2020.101204.

[16]. Schinke, T.; Henze, N.; Boll, S. Visualization of off-screen objects in mobile augmented reality. In Proceedings of the Proceedings of the 12th international conference on Human computer interaction with mobile devices and services, 2010, pp. 313-316.

[17]. Brata, K.C.; Liang, D. An effective approach to develop location-based augmented reality information support. International Journal of Electrical and Computer Engineering (IJECE) 2019, vol 9, pp. 3060-3068. DOI:10.11591/ijece. v9i4.

[18]. Ruta, M.; Scioscia, F.; De Filippis, D.; Ieva, S.; Binetti, M.; Di Sciascio, E. A Semantic-enhanced Augmented Reality Tool for OpenStreetMap POI Discovery. Transportation Research Procedia 2014, vol. 3, pp. 479-488. DOI: 10.1016/j.trpro.2014.10.029.

[19]. Lobo, M.-J.; Christophe, S. Opportunities and challenges for Augmented Reality situated geographical visualization. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2020, V-4-2020. DOI:10.5194/isprs-annals-V-4-2020-163-2020.

[20]. Yang, C.-C.; Sia, W.; Tseng, Y.-C.; Chiu, J.-C. Gamification of Learning in Tourism Industry: A case study of Pokémon Go. In Proceedings of the ACM International Conference Proceeding Series, NEW YORK, 2018, pp. 191-195.

[21]. Paavilainen, J.; Korhonen, H.; Alha, K.; Stenros, J.; Koskinen, E.; Mayra, F. The Pokémon GO Experience. In Proceedings of the Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, 2017, pp. 2493-2498

[22]. Vaittinen, T.; McGookin, D. Uncover: supporting city exploration with egocentric visualizations of location-based content. Personal and Ubiquitous Computing 2018, vol. 22, pp. 807-824.
DOI: https://doi.org/10.1007/s00779-018-1167-9

[23]. Sasaki, R.; Yamamoto, K. A Sightseeing Support System Using Augmented Reality and Pictograms within Urban Tourist Areas in Japan. ISPRS International Journal of Geo-Information 2019, vol. 8.
DOI:10.3390/ijgi8090381.

[24]. Nobrega, R.; Jacob, J.; Coelho, A.; Weber, J.; Ribeiro, J.; Ferreira, S. Mobile location-based augmented reality applications for urban tourism storytelling. 2017; pp. 1-8.

[25]. Paula Alavesa and Timo Ojala. 2015. Street art gangs: location-based hybrid reality game. In Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia (MUM '15). Association for Computing Machinery, New York, NY, USA, 64–74.
DOI: https://doi.org/10.1145/2836041.2836047

[26]. Fang, Z.; Li, Q.; Shaw, S.-L. What about people in pedestrian navigation? Geo-spatial Information Science 2016, vol. 18, pp. 135-150.
DOI:10.1080/10095020.2015.1126071.

[27]. Maslow, A.H. A theory of human motivation. Psychological Review 1943, vol. 50, pp. 370-396.
DOI: https://doi.org/10.1037/h0054346.

[28]. Maslow, A.H. Motivation and personality. Nueva York: Harper & Row, Publishers 1954.

[29]. Maslow, A.H. Toward a psychology of being, 2nd ed; D. Van Nostrand: Oxford, England, 1968, pp. xiii, 240-xiii.

[30]. Hart, S.G.; Staveland, L.E. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research; Elsevier Science & Technology: Amsterdam, The Netherlands, 1988, vol. 52, pp. 139–183.

[31]. Noyes J. M. and Bruneau, D. P. J. A self-analysis of the NASA-TLX workload measure. Ergonomics, 2007, vol. 50, pp.514–519.

[32]. Schrepp, M. User experience questionnaire handbook. All you need to know to apply the UEQ successfully in your project 2015.
Available online: https://www.ueq-online.org/Material/Handbook.pdf

[33]. Schrepp, M. User Experience Questionnaire Handbook; 2015.
DOI: https://doi.org/10.13140/RG.2.1.2815.0245

[34]. Montello, D.R. Spatial cognition. In International Encyclopedia of the Social and Behavioral Sciences, Smelser, N.J., Baltes, B., Eds.; 2001, pp. 7--14771.

[35]. Allen, G.L. Spatial abilities, cognitive maps, and wayfinding. Wayfinding behavior: Cognitive mapping and other spatial processes 1999, pp. 46-80.

[36]. Allen, G.L. Cognitive abilities in the service of wayfinding: A functional approach. The Professional Geographer 1999, vol. 51, pp. 555-561.

[37]. Wiener, J. M., Büchner, S. J. & Hölscher, C. Taxonomy of human wayfinding tasks: A knowledge-based approach. Spat. Cogn. Comput. 2009, vol. 9, pp. 152–165.
DOI: 10.1080/13875860902906496

[38]. Milgram, P., Takemura, H., Utsumi, A. & Kishino, F. Augmented reality: A class of displays on the reality-virtuality continuum. In Das, H. (ed.) SPIE Proceedings, 1995.
DOI:https:// doi. org/ 10. 1117/ 12. 197321

[39]. Azuma, R. Making Augmented Reality a Reality. JTu1F.1, 2017.
DOI: 10.1364/3D.2017.JTu1F.1.

[40]. Sutherland, I.E. A Head-Mounted Three-Dimensional Display. In Proceedings of the Fall Joint Computer Conference, PartI—Association for Computing Machinery, AFIPS ’68 (Fall, Part I), New York, NY, USA, 9–11 December 1968; pp. 757–764.
DOI: https://doi.org/10.1145/1476589.1476686

[41]. Hololens.
Available online: https://www.microsoft.com/ja-jp/hololens

[42]. Brata, K.C.; Liang, D. An effective approach to develop location-based augmented reality information support. International Journal of Electrical and Computer Engineering (IJECE) 2019, vol 9, pp. 3060-3068.
DOI:10.11591/ijece. v9i4.

[43]. Carmo, M.; Afonso, A.; Ferreira, A.; Cláudio, A.P.; Silva, G. PoI Awareness, Relevance and Aggregation for Augmented Reality; 2016, pp. 300-305.

[44]. Google Map.

Available online: https://www.google.com

[45]. Google Street View.

Available online: https://www.google.com/streetview/

[46]. Google Earth.

Available online: https://www.google.co.jp/intl/ja/earth/

[47]. Bekele, M.K.; Pierdicca, R.; Frontoni, E.; Malinverni, E.S.; Gain, J. A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage. Journal on Computing and Cultural Heritage 2018, vol. 11, pp. 1-36.
DOI:10.1145/3145534.

[48]. Bekele, M.K. Walkable Mixed Reality Map as interaction interface for Virtual Heritage. Digital Applications in Archaeology and Cultural Heritage 2019, vol. 15.
DOI: 10.1016/j.daach. 2019.e00127.

[49]. Boutsi, A.; Ioannidis, C.; Soile, S. HYBRID MOBILE AUGMENTED REALITY: WEB-LIKE CONCEPTS APPLIED TO HIGH RESOLUTION 3D OVERLAYS. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2019.
DOI:10.5194/isprs-archives-XLII-2-W17-85-2019.

[50]. Boustila, S.; Ozkan, M.; Bechmann, D. Interactions with a Hybrid Map for Navigation Information Visualization in Virtual Reality; 2020; pp. 69-72.

[51]. Deterding, S.;Dixon, D.; Khaled, R.; Nacke, L. From game design elements to gamefulness: Defining "gamification". In Pro-ceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments, Tampere, Finland, 28–30 September 2011, pp. 9–15.
DOI: https://doi.org/10.1145/2181037.2181040.

[52]. Bartley, J.; Forsyth, J.; Pendse, P.; Xin, D.; Brown, G.; Hagseth, P.; Agrawal, A.; Goldberg, D.; Hammond, T. World of workout: a contextual mobile RPG to encourage long term fitness, 2013.

[53]. Orji, R.; Nacke, L.; Di Marco, C. Towards Personality-driven Persuasive Health Games and Gamified Systems. 2017, pp. 1015-1027.

DOI: https://doi.org/10.1145/3025453.3025577.

[54]. Göschlberger, B.; Bruck, P. Gamification in mobile and workplace integrated microlearning. 2017, pp. 545-552.
DOI: https://doi.org/10.1145/3151759.3151795.

[55]. Swacha, J.; Muszyńska, K. Towards a Generic eGuide Gamification Framework for Tourist Attractions. In Proceedings of the 2018 Annual Symposium on

Computer-Human Interaction in Play Companion Extended Abstracts, Melbourne, Australia, 28–31 October 2018; ACM: Melbourne, Australia, 2018, pp. 619–625. DOI: https://doi.org/10.1145/3270316.3271535.

[56]. Arkenson, C., Chou, Y. Y., Huang, C. Y., & Lee, Y. C. Tag and seek: a location-based game in tainan city. In CHIplay'24, 2014, pp. 315-318. DOI: https://doi.org/10.1145/2658537.2662986.

[57]. C. Pang, R. Pan, S. Wong, C. Neustaedter, and Y. Wu, "City Explorer: Gamifying Public Transit Trips While Exploring the City.", Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '17, ACM Press, 2017, pp.2825–2832. DOI: https://doi.org/10.1145/3027063.3053252.

[58]. Rubino, I.; Barberis, C.; Xhembulla, J.; Malnati, G. Integrating a location-based mobile game in the museum visit: Evaluating visitors' behavior and learning. J. Comput. Cultur. Herit. 2015,8, pp. 1–18. DOI: https://doi.org/10.1145/2724723.

[59]. Paula Alavesa and Timo Ojala. 2015. Street art gangs: location based hybrid reality game. In Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia (MUM '15). Association for Computing Machinery, New York, NY, USA, 64–74. https://doi.org/10.1145/2836041.2836047

[60]. Ye, M.; Yin, P.; Lee, W.C.; Lee, D.L. Exploiting geographical influence for collaborative point-of-interest recommendation. In Proceedings of the SIGIR'11—34th International ACM SIGIR Conference on Research and Development in Information, Beijing, China, 25–29 July 2011, pp. 325–334. DOI: https://doi.org/10.1145/2009916.2009962.

[61]. Baltrunas, L.; Ludwig, B.; Peer, S.; Ricci, F. Context relevance assessment and exploitation in mobile recommender systems. Pers.Ubiquitous Comput. 2011, vol. 16, pp. 507–526 DOI: https://doi.org/10.1007/s00779-011-0417-x

[62]. Perebner, M.; Huang, H.; Gartner, G. Applying user-centred design for smartwatch-based pedestrian navigation system. Journal of Location Based Services 2019, vol. 13, pp. 213-237. DOI:10.1080/17489725.2019.1610582.

[63]. Huang, H.; Mathis, T.; Weibel, R. Choose your own route – supporting pedestrian navigation without restricting the user to a predefined route. Cartography and Geographic Information Science 2021, vol. 49, pp. 1-20. DOI:10.1080/15230406.2021.1983731.

[64]. Herzog, D.; Sikander, S.; Worndl, W. Integrating route attractiveness attributes into tourist trip recommendations. In Proceedingsof the 2019 World Wide Web Conference, San Francisco, California, 13–17 May 2019, pp. 96–101, DOI :10.1145/3308560.3317052.

[65]. Weber, J. "Designing engaging experiences with location-based augmented reality games for urban tourism environments." 2017.

[66]. Rehrl, K.; Häusler, E.; Leitinger, S.; Bell, D. Pedestrian navigation with augmented reality, voice and digital map: final results from an in-situ field study assessing performance and user experience. Journal of Location Based Services 2014, vol. 8, pp. 75-96. DOI:10.1080/17489725.2014.946975.

[67]. Al Rabbaa, J., Morris, A., Somanath, S. (2019). MRsive: An Augmented Reality Tool for Enhancing Wayfinding and Engagement with Art in Museums. In: Stephanidis, C. (eds) HCI International 2019 - Posters. HCII 2019. Communications in Computer and Information Science, vol. 1034. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-23525-3_73

[68]. Norman, D. A. and S. W. Draper. User Centered System Design; New Perspectives on Human-Computer Interaction, L. Erlbaum Associates Inc: 1986.

[69]. Gemperle, F., C. Kasabach, J. Stivoric, M. Bauer and R. Martin. Design for wearability. Digest of Papers. Second International Symposium on Wearable Computers (Cat.No.98EX215). 1998, pp. 116-122. DOI:10.1109/ISWC.1998.729537

[70]. Lee, L.-H.; Braud, T.; Hosio, S.; Hui, P. Towards Augmented Reality-driven Human-City Interaction: Current Research on Mobile Headset and Future Challenges; 2020.

[71]. Zhang, Y.; Cao, Y.; Nakajima, T. Engaging New Residents' City Exploration Using a Gamified Location-Based Information Interactive System. In Proceedings of the Human-Computer Interaction. Theory, Methods and Tools: Thematic Area, HCI 2021, Held as Part of the 23rd HCI International Conference, HCII 2021, Virtual Event, July 24–29, 2021, Proceedings, Part I, 2021, pp. 412–428.

[72]. Unity 3D.
Available online: https://unity.com/ja

[73]. Vuforia SDK.
Available online: https://developer.vuforia.com/downloads/SDK

[74]. Zhang, Y.; Nakajima, T. Exploring the Design of a Mixed-Reality 3D Minimap to Enhance Pedestrian Satisfaction in Urban Exploratory Navigation. Future Internet 2022, Volume 14, Issue 11:325, 24 pages. DOI:10.3390/fi14110325

[75]. Khan, N.; Rahman, A.U. Rethinking the Mini-Map: A Navigational Aid to Support Spatial Learning in Urban Game Environments. International Journal of Human–Computer Interaction 2017, vol. 34, pp. 1135-1147. DOI:10.1080/10447318.2017.1418804.

[76]. Toups, Z.; Lalone, N.; Alharthi, S.; Sharma, H.; Webb, A. Making Maps Available for Play: Analyzing the Design of Game Cartography Interfaces. ACM transactions on computer-human interaction 2019, vol. 26, pp. 1-43. DOI:10.1145/3336144.

[77]. Zagata, K.; Gulij, J.; Halik, Ł.; Medyńska-Gulij, B. Mini-Map for Gamers Who Walk and Teleport in a Virtual Stronghold. ISPRS International Journal of Geo-Information 2021, 10.
DOI:10.3390/ijgi10020096.

[78]. Xcode.
Available online: https://developer.apple.com/xcode/

[79]. MapKit.
Available online: https://developer.apple.com/documentation/mapkit/

[80]. ARKit.
Available online: https://developer.apple.com/augmented-reality/arkit/

[81]. Gushima, K.; Nakajima, T. Virtual Fieldwork: Designing Augmented Reality Applications Using Virtual Reality Worlds. Lecture Notes in Computer Science; Springer International Publishing: Cham, 2021, vol. 12770, pp. 417-430.

[82]. Gushima, K.; Nakajima, T. A Scenario Experience Method with Virtual Reality Technologies for Designing Mixed Reality Services. NEW YORK, 2020, pp. 122-125.

[83]. Li, C. User preferences, information transactions and location-based services: A study of urban pedestrian wayfinding. Computers, environment and urban systems 2006, vol. 30, pp. 726-740
DOI: 10.1016/j.compenvurbsys.2006.02.008.

[84]. König, S.U.; Keshava, A.; Clay, V.; Rittershofer, K.; Kuske, N.; König, P. Embodied Spatial Knowledge Acquisition in Immersive Virtual Reality: Comparison to Map Exploration. Frontiers in virtual reality 2021, vol. 2.
DOI:10.3389/frvir.2021.625548.
DOI: 10.1016/j.buildenv.2020.107329.

[85]. Stähli, L.; Giannopoulos, I.; Raubal, M. Evaluation of pedestrian navigation in Smart Cities. Environment and planning. B, Urban analytics and city science 2021, vol. 48, pp. 1728-1745.
DOI:10.1177/2399808320949538.

[86]. Török, Z.G.; Török, A.; Tölgyesi, B.; Kiss, V. The virtual tourist: Cognitive strategies and differences in navigation and map use while exploring an maginary city. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 2018, vol. 42, pp. 703-709.
DOI:10.5194/isprs-archives-XLII-4-631-2018.

[87]. Oculus quest 2.
Available. online: https://store.facebook.com/jp/quest/products/quest-2/

[88]. Wilcoxon, F. Individual comparisons by ranking methods. In Breakthroughs in statistics; Springer: 1992, pp. 196-202.

[89]. Credé, S.; Thrash, T.; Hölscher, C.; Fabrikant, S.I. The advantage of globally visible landmarks for spatial learning. Journal of Environmental Psychology 2020, vol. 67.
DOI: 10.1016/j.jenvp.2019.101369.

[90]. Elias, B.; Paelke, V. User-Centered Design of Landmark Visualizations. In Map-based Mobile Services; Lecture Notes in Geoinformation and Cartography; 2008, pp. 33-56.

[91]. Santana, J.M.; Wendel, J.; Trujillo, A.; Suárez, J.P.; Simons, A.; Koch, A. Multimodal Location Based Services—Semantic 3D City Data as Virtual and Augmented Reality. In Progress in Location-Based Services 2016; Lecture Notes in Geoinformation and Cartography; 2017, pp. 329-353.

[92]. Snowdon, C.; Kray, C. Exploring the use of landmarks for mobile navigation support in natural environments. In Proceedings of the International Conference

on Human-Computer Interaction with Mobile Devices and Services, 2009, pp. 1-10.

[93]. Jylhä, A.; Hsieh, Y.-T.; Orso, V.; Andolina, S.; Gamberini, L.; Jacucci, G. A wearable multimodal interface for exploring urban points of interest. In Proceedings of the Proceedings of the 2015 ACM on International Conference on Multimodal Interaction, 2015, pp. 175-182.

[94]. Besharat, J.; Komninos, A.; Papadimitriou, G.; Lagiou, E.; Garofalakis, J. Augmented paper maps: Design of POI markers and effects on group navigation. Journal of Ambient Intelligence and Smart Environments 2016, vol. 8, pp. 515-530.

LIST OF PUBLICATIONS

Zhang, Y.; Nakajima, T. Exploring the Design of a Mixed-Reality 3D Minimap to Enhance Pedestrian Satisfaction in Urban Exploratory Navigation. Future Internet 2022, Volume 14, Issue 11:325, 24 pages.

DOI:10.3390/fi14110325

Zhang, Y.; Cao, Y.; Nakajima, T. Engaging New Residents' City Exploration Using a Gamified Location-Based Information Interactive System. HCII 2021, Virtual Event, July 24–29, 2021; Proceedings, Part I, 2021; pp.412-428.

DOI: 10.1007/978-3-030-78462-1_32

Cao, Y.; Zhang, Y.; Nakajima, T. Improving Information Acquisition in City Tours via Simplified Virtual Scenes with Location-Based POIs. HCII 2022, Proceedings. Springer Science and Business Media Deutschland GmbH. 2022. pp. 37-52.

DOI: 10.1007/978-3-031-05431-0_3

Zhang, Y.; Nakajima, T. Exploring 3D Landmark-based Map Interface in Augmented reality Navigation System for City Exploration; In Proceedings of the 20th International Conference on Mobile and Ubiquitous Multimedia, MUM 2021. pp. 220-222.

DOI: 10.1145/3490632.3497858

Zhang, Y.; Nakajima, T. Gamified navigation system: Enhancing resident user experience in city exploration. In UbiComp/ISWC 2020 Adjunct - Proceedings of the 2020 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2020 ACM International Symposium on Wearable Computers. Association for Computing Machinery. 2020. pp. 180-183.

DOI: 10.1145/3410530.3414405